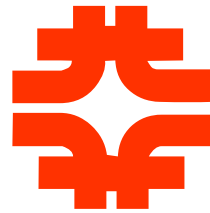
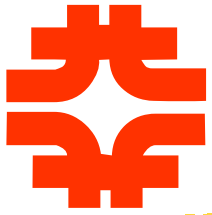


Status of the Pbar Source



Dave McGinnis
AAC Meeting
May 13, 2002



Overview

- The present pbar production rate which is at 60% of the design value is adequate to support present Run II operations.
- The horizontal emittance of a typical 100E+10 antiproton stack is about a factor of 2 larger than the Run II handbook design value.
 - At a stack of 100E+10 pbars the normalized horizontal transverse emittance is about 17π -mm-mrad.
 - The Run II handbook specifies 8π -mm-mrad at 100E+10 pbars
- For the past 5 months, almost 100% of the manpower and machine study time of the Pbar Source department has been devoted to trying to reduce the horizontal emittance.
- We believe that the horizontal emittance growth is caused by
 - Intra-beam scattering (60%)
 - Trapped ions (40%)
- The intra-beam scattering (IBS) heating of the beam is worse now for Run II than it was in Run I because of the changes in beta functions that were the result of the Accumulator Lattice Upgrade



Overview

- We have developed a two-fold plan to reduce the transverse emittance:
 - Better transverse stochastic cooling of the Accumulator core.
 - The bandwidth will increase by a factor of 2
 - The center frequency of the band will increase by a factor of 1.5
 - Dual lattice operation mode of the Accumulator
 - Keep the “fast stacking” lattice ($\eta=0.012$) for pbar production
 - During shot setup, ramp the lattice with the beam at the core orbit to the “IBS” lattice ($\eta=0.022$)
 - The “IBS” lattice will reduce the intra-beam scattering heating by a factor of 2.5
 - The “IBS” lattice will increase the cooling rate by a factor of two increase in mixing due to the change in η

$$\frac{d\epsilon}{dt} \approx -\frac{\epsilon}{\tau_{\text{cool}}} + \frac{\text{Heat}}{\epsilon^{3/2}}$$

$$\frac{\epsilon_{\text{old}}}{\epsilon_{\text{new}}} = \left(\frac{\tau_{\text{cool}_{\text{old}}}}{\tau_{\text{cool}_{\text{new}}}} \frac{\text{Heat}_{\text{old}}}{\text{Heat}_{\text{new}}} \right)^{2/5} = \underbrace{(2}_{\text{Bandwidth}} \times \underbrace{1.5}_{\text{Center freq.}} \times \underbrace{2}_{\text{Better Mixing}})^{2/5} \times \left(\frac{\overbrace{0.4 + 0.6}^{\text{Ions}}}{\underbrace{0.4 + \frac{0.6}{2.5}}_{\text{Reduced IBS}}} \right)^{2/5} = 2.4$$

Center freq.
Ions
IBS

Bandwidth
Better Mixing
Reduced IBS



Pbar Source Near Term Plans*

- Commission Dual Lattice mode in Accumulator
 - Begin commissioning 5/14/02
 - First practice shot by 6/2/02
 - Finish commissioning by 6/30/02
- Install Accumulator Core Cooling Upgrade
 - Tunnel installation 6/3/02 – 6/14/02
 - System commissioning 6/15/02 – 6/16/02
- Reduce pbar production cycle time
 - Install Debuncher momentum narrowband filters 7/02
 - Commission Stacktail-Core compensation legs 7/02
- Begin AP2 Aperture studies 8/02

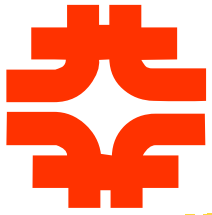
*depends on the wind



P1-AP3 8 GeV Optics

(a success story)

- The P1-AP3 8 GeV transfer line connects the Accumulator with the Main Injector.
- Because of its long length (900 m), tri-energy mode operation (8 GeV, 120 GeV, 150 GeV), and severe hysteresis problems at 8 GeV, this line has been extremely difficult to commission and operate.
- During the fall of 2001, a large number of beam optics measurements were performed on the P1-AP3 8 GeV transfer line
- Based on these measurements, a new set of optics settings were installed in January of 2002.
- The collider luminosity increased ~20% as a result of these changes.
- With these new settings in place, further tuning of the quads closest to the Main Injector has resulted in a 25% decrease in emittance dilution for reverse 8 GeV protons injected into the Accumulator.
- **These changes had NO positive impact on measured Main Injector 8 GeV emittance or Collider luminosity**



Accumulator Run II “Upgrades”

(why did we change the Accumulator Lattice)

- Main Injector Project was to increase the antiproton flux into the Accumulator by a factor of 2.7
 - A factor of 1.7 increase in the number of protons on target
 - A factor of 1.6 increase in 120 GeV proton production rate

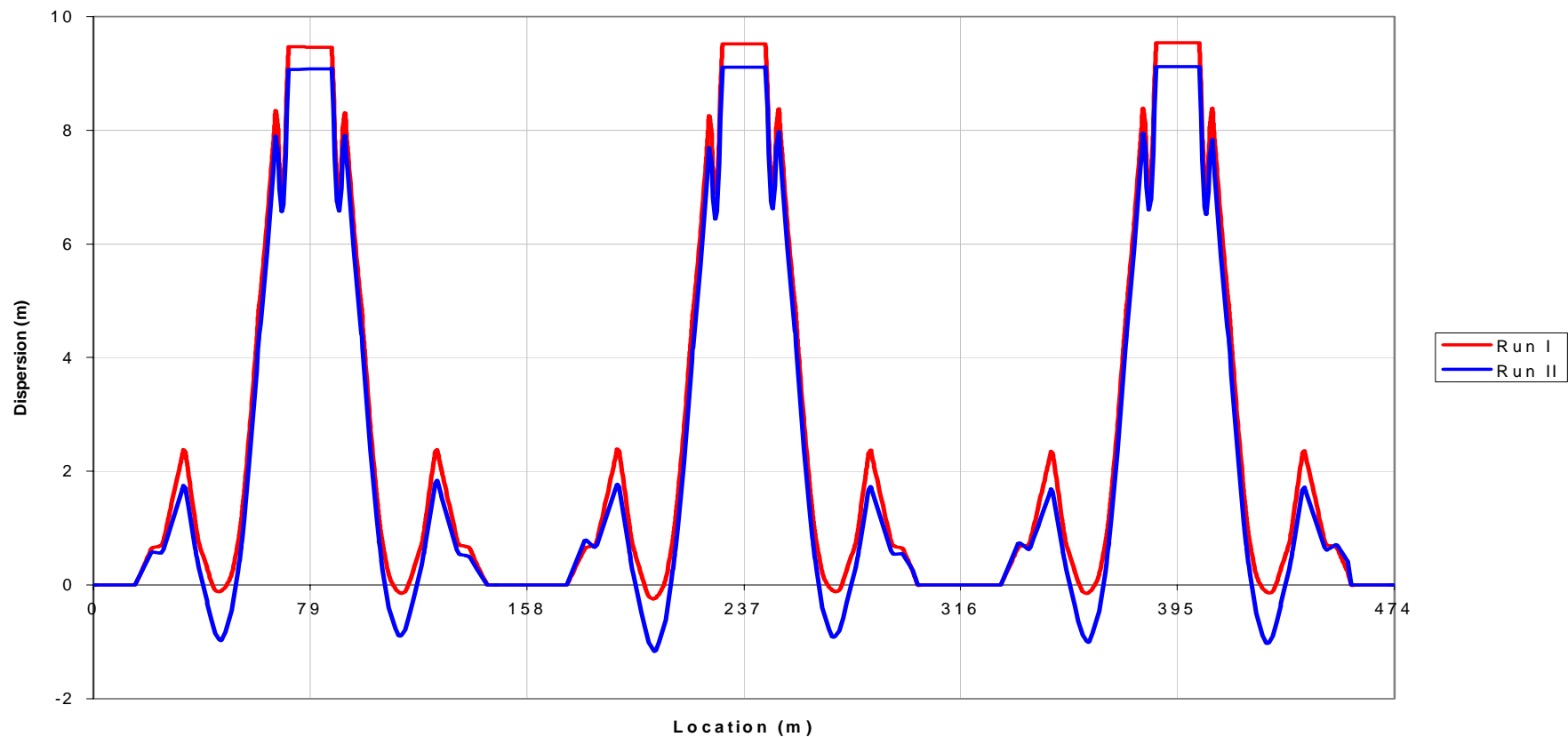
$$\Phi = \frac{W^2 \eta E_d}{f_0 p \ln\left(\frac{F_{\min}}{F_{\max}}\right)}$$

Antiproton flux through the Accumulator
Stacktail Momentum Stochastic Cooling
system

- Bandwidth W to increase from 1-2 GHz to 2-4 GHz
 - 15 meters of new Stacktail Pickup Arrays in A60
 - 15 meters of new Stacktail Kicker Arrays in A30
- Changed Accumulator lattice to keep Stacktail system stable
 - Schottky bands must not overlap in the Stacktail frequency range
 - Maximum frequency of the Stacktail system increased from 2 GHz to 4 GHz
 - η must decrease from the Run I value of 0.022 to 0.012 in Run II
 - γ_t must increase from the Run I value of 5.5 to 6.55 in Run II



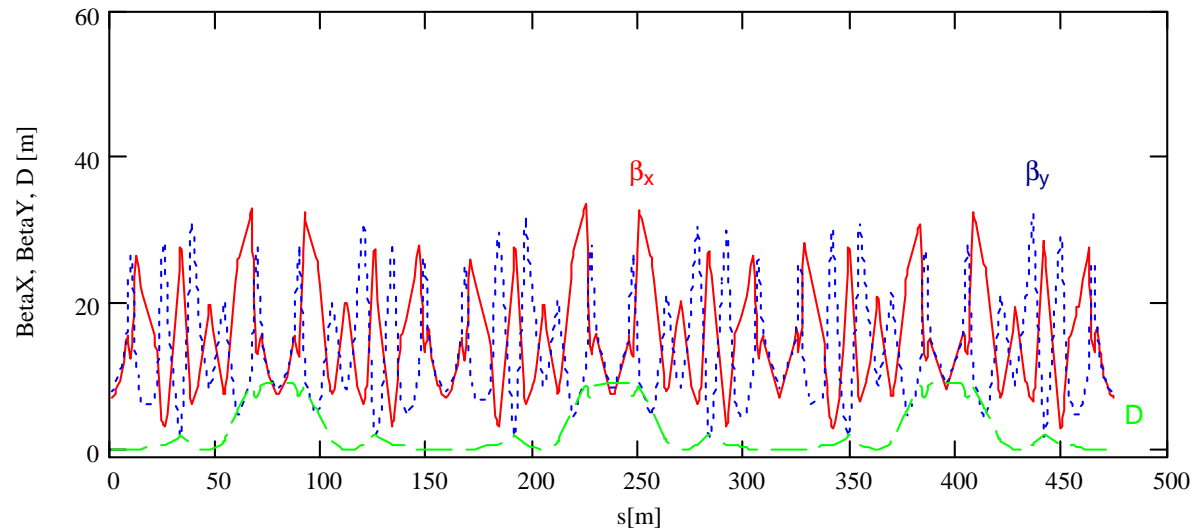
Accumulator Lattice Upgrade



- γ_t increase was obtained by adding negative dispersion at the “B7” bends
- Shunts were added to 6 of the 14 quads in each of six sectors
- The quads on either side of each of the high dispersion straight sections were increased in strength

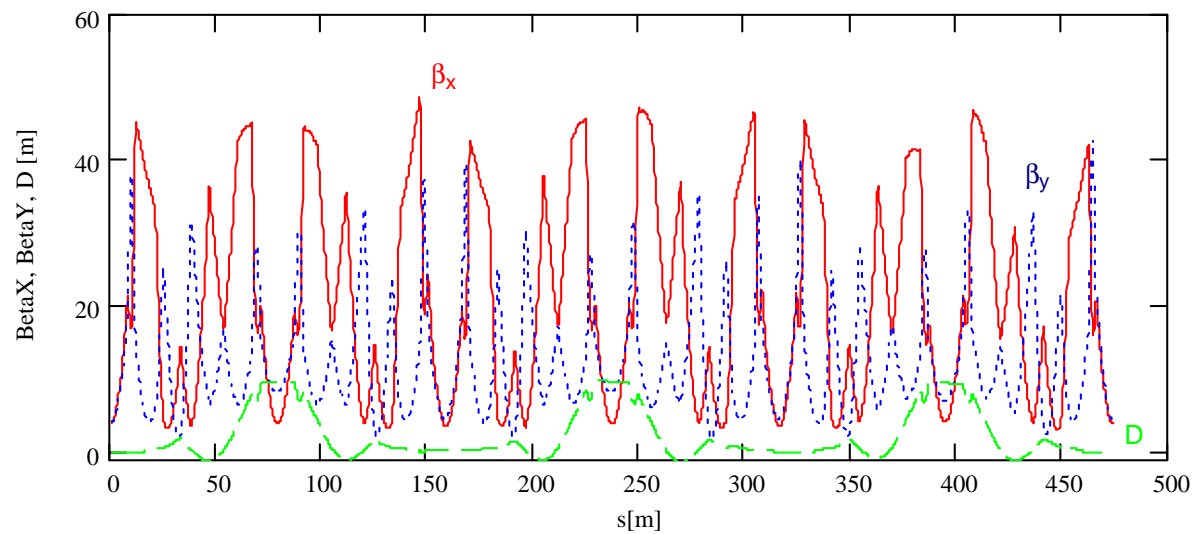


Accumulator Lattice Upgrade



Run I Lattice

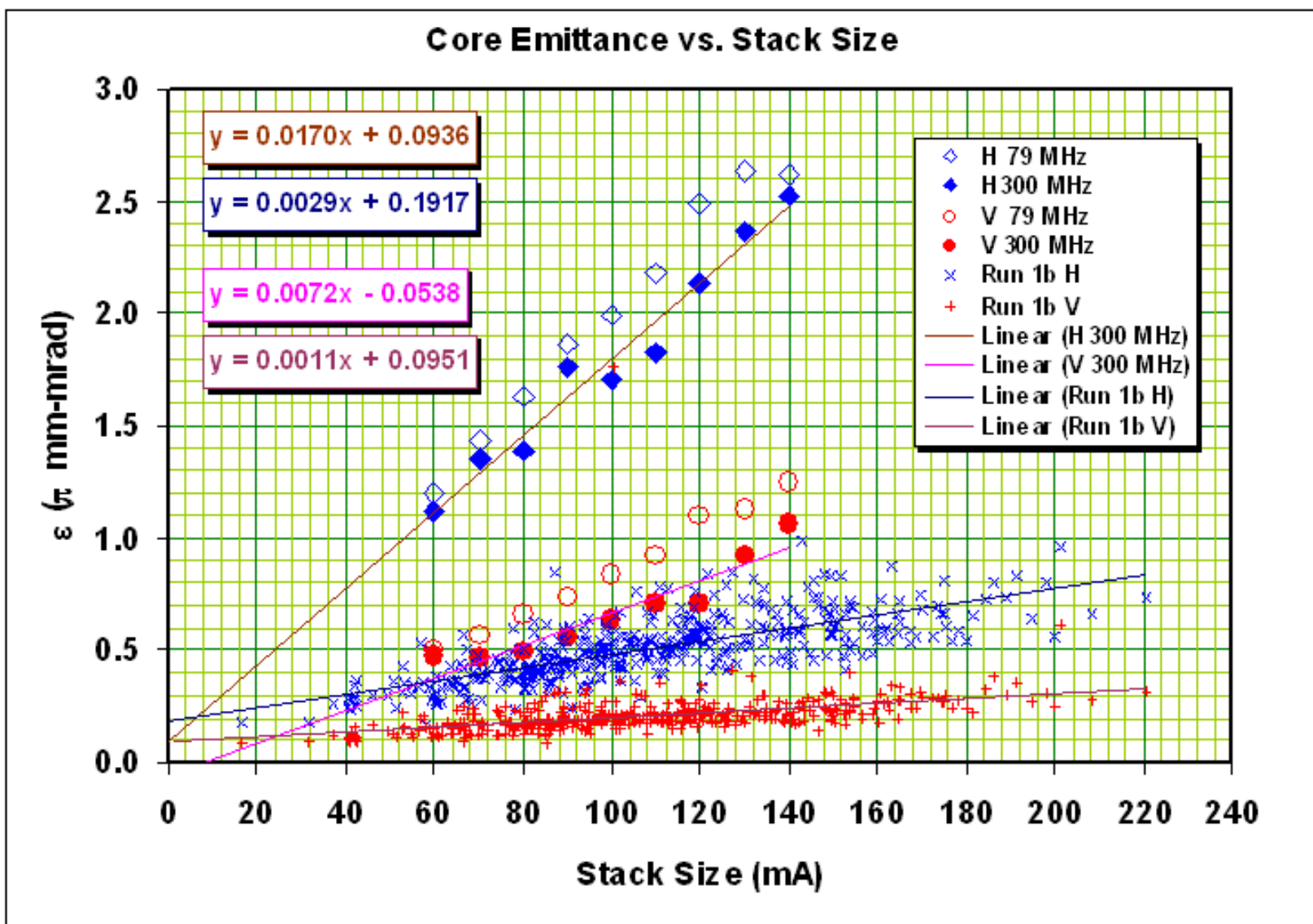
	Old	New
β_x [m]	15.3	20.9
β_y [m]	13.4	12.5



Run II Lattice

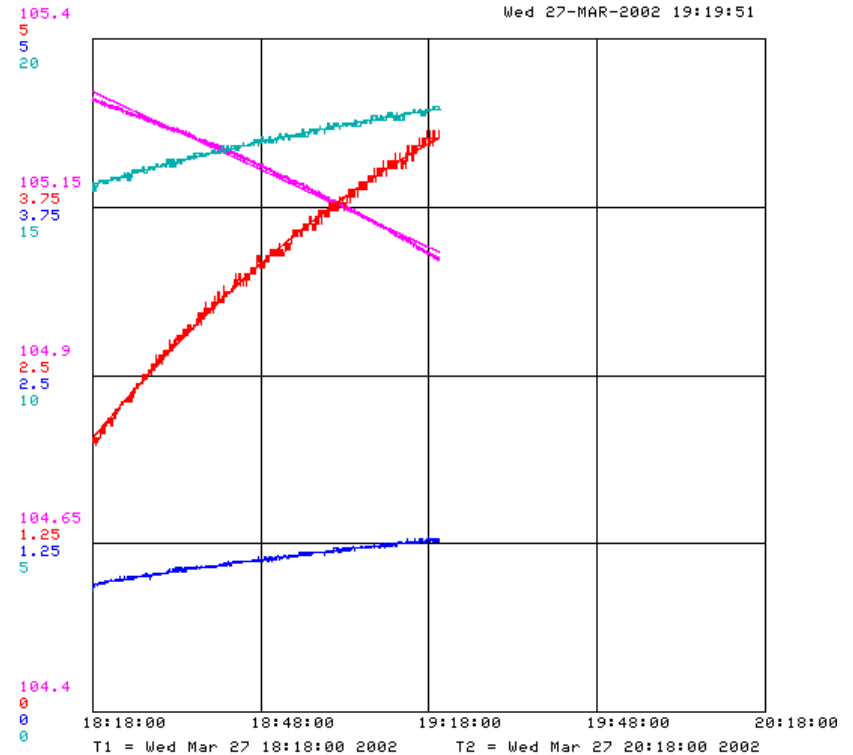
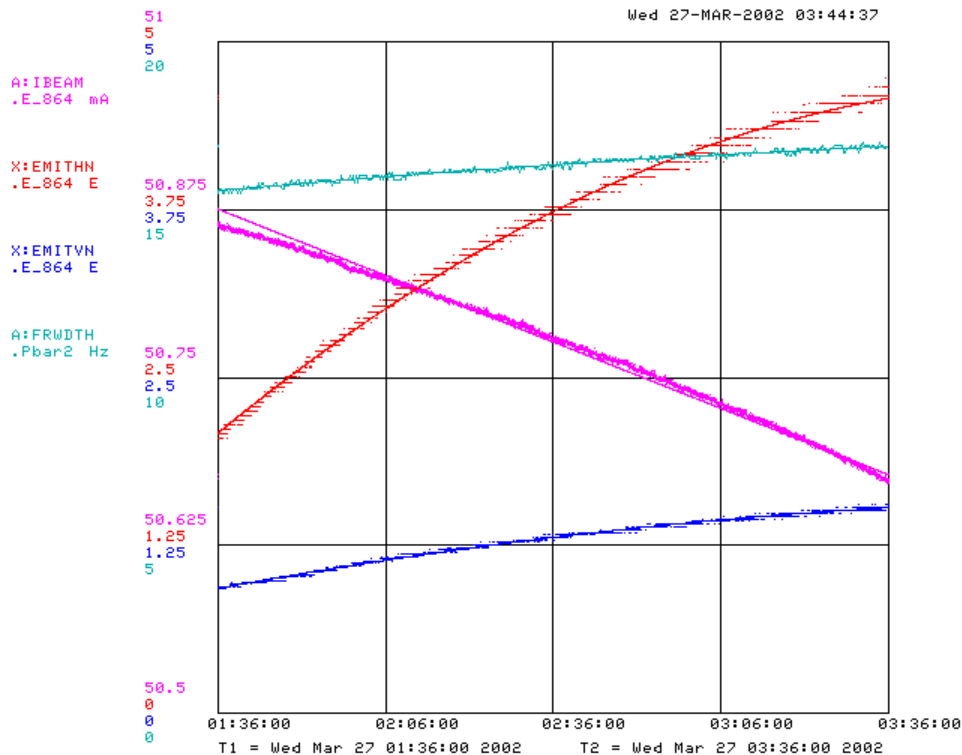


Transverse Emittance

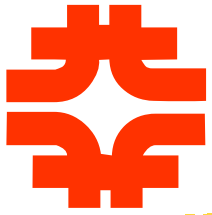




Emittance Growth Rate without Cooling



- Growth rate mostly in the horizontal plane
- Growth rate increases with intensity
 - $2 \pi\text{-mm-mrad/hr}$ @ 50 mA
 - $3 \pi\text{-mm-mrad/hr}$ @ 100 mA
- Growth rate decreases with beam size
 - $3 \pi\text{-mm-mrad/hr}$ @ $2 \pi\text{-mm-mrad}$
 - $1.6 \pi\text{-mm-mrad/hr}$ @ $4 \pi\text{-mm-mrad}$
- Growth rate is bigger for pbars than reverse protons



Possible Sources of Emittance Growth

- External Noise Sources

- ☐ Damper noise
- ☐ Electronic noise in the stochastic cooling systems
- ☐ Kicker Voltage noise
- ☐ Power supply ripple
- ☐ Oscillating pre-amps on BPMs
- ☐ Etc.

- Betatron Tunes

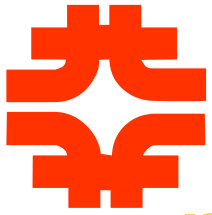
- ☐ Located on high order resonances
- ☐ Influenced by strong low order stop-band widths (3rd order in the case of the Accumulator)

- Vacuum

- Instabilities

- Trapped ions

- Intra-beam scattering



Emittance Studies

No.	Title	Date	Category
1	Reverse Protons	12/12/2001	P1-AP3 Lattice
2	Pbar Transverse Heating and Cooling Studies	12/16/2001	Transverse Emittance Growth Rate Measurements
3	Transverse Heating vs. Stack Size	12/19/2001	Transverse Emittance Growth Rate Measurements
4	General beam heating investigation	12/20/2001	Transverse Emittance Growth Rate Measurements
5	Test of New 300 MHz PU	12/28/2001	300 MHz Emittance Monitor
6	Tunes across the momentum aperture	1/3/2002	Tunes Across the Momentum Aperture
7	Accumulator 1 bump measurements	1/3/2002	Accumulator Lattice Measurements
8	Attempting new 8GeV reverse proton lattice P1-AP3	1/7/2002	P1-AP3 Lattice
9	Emittance Growth with Protons and Pbars	1/8/2002	Transverse Emittance Growth Rate Measurements
10	New 8GeV lattice	1/15/2002	P1-AP3 Lattice
11	Continuation 8 GeV lattice studies	1/16/2002	P1-AP3 Lattice
12	AP3 optics study with reversed protons	1/22/2002	P1-AP3 Lattice
13	8GeV Trim calibrations for P1 and P2 lines	1/23/2002	P1-AP3 Lattice
14	Accumulator Tunes vs. dp/p	1/24/2002	Tunes Across the Momentum Aperture
15	Next round of optics corrections	1/24/2002	P1-AP3 Lattice
16	The latest new 8GeV P1-AP3 lattice and profile measurements	1/29/2002	P1-AP3 Lattice
17	Accumulator Tune Scans	1/29/2002	Tunes Across the Momentum Aperture
18	Quad centers in P1 & P2	1/30/2002	P1-AP3 Lattice
19	Steering of reverse protons into accumulator	2/5/2002	P1-AP3 Lattice
20	300 MHz Emittance Monitor Measurements	2/6/2002	300 MHz Emittance Monitor
21	Pbar Unstacking RF Studies	2/12/2002	Pbar RF Unstacking Studies
22	Pbar Unstacking Studies	2/13/2002	Pbar RF Unstacking Studies
23	8GeV P1-AP3-Acc studies	2/18/2002	P1-AP3 Lattice
24	ARF4 Unstacking studies	2/19/2002	Pbar RF Unstacking Studies
25	Continuation of Unstacking studies	2/20/2002	Pbar RF Unstacking Studies
26	Extraction studies	2/21/2002	Pbar RF Unstacking Studies
27	Emittance growth vs. tunes	2/21/2002	Transverse Emittance Growth Rate Measurements
28	Pbar Shots with new RF curves	2/24/2002	Pbar RF Unstacking Studies
29	Emittance vs Stack Size	3/6/2002	Transverse Emittance Growth Rate Measurements



Emittance Studies

No.	Title	Date	Category
30	Accumulator 300 MHz Emittance Monitor Calibration	3/7/2002	300 MHz Emittance Monitor
31	Three-D Phase Space Density Measurements	3/11/2002	Transverse Emittance Growth Rate Measurements
32	Coupling Accumulator tunes	3/11/2002	Transverse Emittance Growth Rate Measurements
33	Beam to the central orbit	3/19/2002	Transverse Emittance Growth Rate Measurements
34	Accumulator 3rd order Harmonic Correction	3/20/2002	Transverse Emittance Growth Rate Measurements
35	Inter Beam Scattering Study	3/25/2002	IBS Measurements
36	Pbar Emittance growth at 50 mA	3/26/2002	IBS Measurements
37	Intrabeam Scattering Measurement	3/27/2002	IBS Measurements
38	Intrabeam Scattering Studies	3/27/2002	IBS Measurements
39	Extraction orbit betas near ELAM	4/1/2002	P1-AP3 Lattice
40	300 MHz Emittance Monitor Calibration (Again and Again)	4/2/2002	300 MHz Emittance Monitor
41	Pbar Extraction Studies	4/2/2002	Tunes Across the Momentum Aperture
42	Tunes vs. emittances	4/4/2002	Transverse Emittance Growth Rate Measurements
43	Accumulator IBS lattice Studies	4/9/2002	IBS Measurements
44	Accumulator IBS lattice Studies	4/9/2002	IBS Measurements
45	Accumulator IBS lattice Studies	4/10/2002	IBS Measurements
46	Tunes and more tunes, and lifetime	4/10/2002	Transverse Emittance Growth Rate Measurements
47	Attempt at IBS studies	4/16/2002	IBS Measurements
48	IBS new lattice studies, with chromaticity corrections	4/17/2002	IBS Measurements
49	IBS new lattice studies, with chromaticity corrections	4/18/2002	IBS Measurements
50	Test of Vertical Thermostat	4/21/2002	IBS Measurements
51	Accumulator Chromaticity correction	4/22/2002	Tunes Across the Momentum Aperture
52	Lattice match, Main Injector to Accumulator	4/23/2002	P1-AP3 Lattice
53	Looking for rogue devices	4/23/2002	Transverse Emittance Growth Rate Measurements
54	MI to Accumulator lattice match	4/25/2002	P1-AP3 Lattice
55	Main Injector to Accumulator lattice match	4/29/2002	P1-AP3 Lattice
56	Measure Accumulator Tunes vs. dp/p	4/30/2002	Tunes Across the Momentum Aperture
57	Emittance growth by heating the beam	4/30/2002	Transverse Emittance Growth Rate Measurements
58	Emittance growth -- once again	4/30/2002	IBS Measurements



Planning Pbar Studies

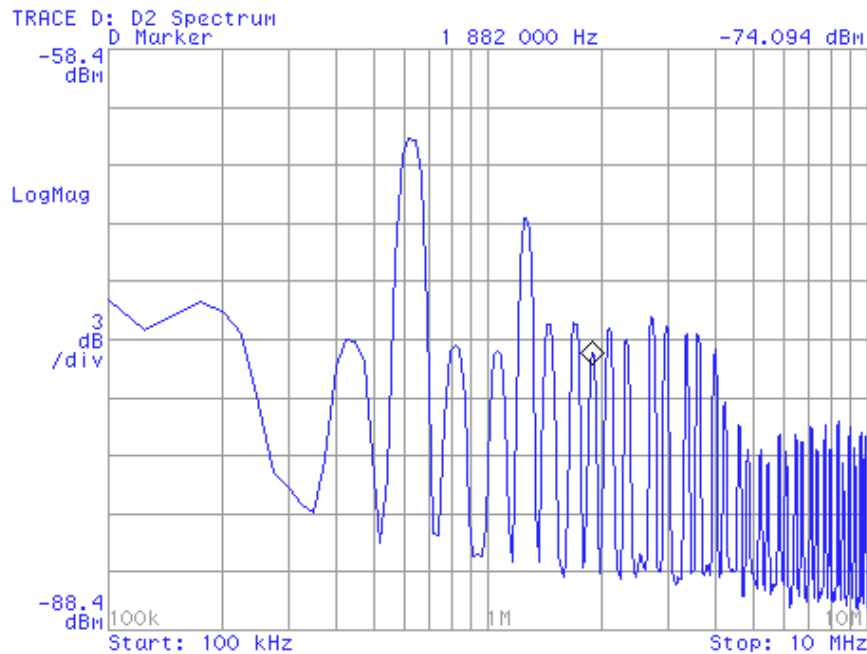
- **Pbar Studies**
 - ❑ Contiguous 5 shift period
 - ❑ Usually spend 1 shift stacking
 - ❑ Usually spend 1 shift supporting TEV or Recycler
 - ❑ Average 3 shifts of dedicated studies
- **Pbar Dept. Study meeting**
 - ❑ Thursday morning 9:00 am
 - ❑ Review past week studies
 - ❑ Pre-plan next week studies
- **Beams Division operations meeting**
 - ❑ Monday morning 9:00 am
 - ❑ Rough schedule for the week outlined
- **Pbar Dept. Study meeting**
 - ❑ Monday morning 9:30 am
 - ❑ Pbar study plans, schedule, and manpower finalized
- **Beams Division Studies Planning Meeting**
 - ❑ Monday morning 10:30 am
 - ❑ Schedule with other machine groups coordinated
- **Beams Division Run II Commissioning meeting**
 - ❑ Sometimes report on study results to the division



External Noise Sources

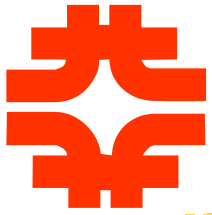
- A growth rate of $0.5 - 1 (\pi\text{-mm-mrad/hr}) / (\mu\text{W/Hz})$ is measured when an external noise source is applied with a transverse wideband 50 Ohm kicker at single betatron lines.
- A signal of $0.2 \mu\text{W/Hz}$ applied to a transverse kicker can be seen on the damper pickups with a stack size of $100\text{E}+10$ pbars.
- With the exception of the 1-Q line, no betatron line is observed on the damper pickups at $100\text{E}+10$ pbars.

10 $\mu\text{W/Hz}$ at $25\text{E}+10$ pbars



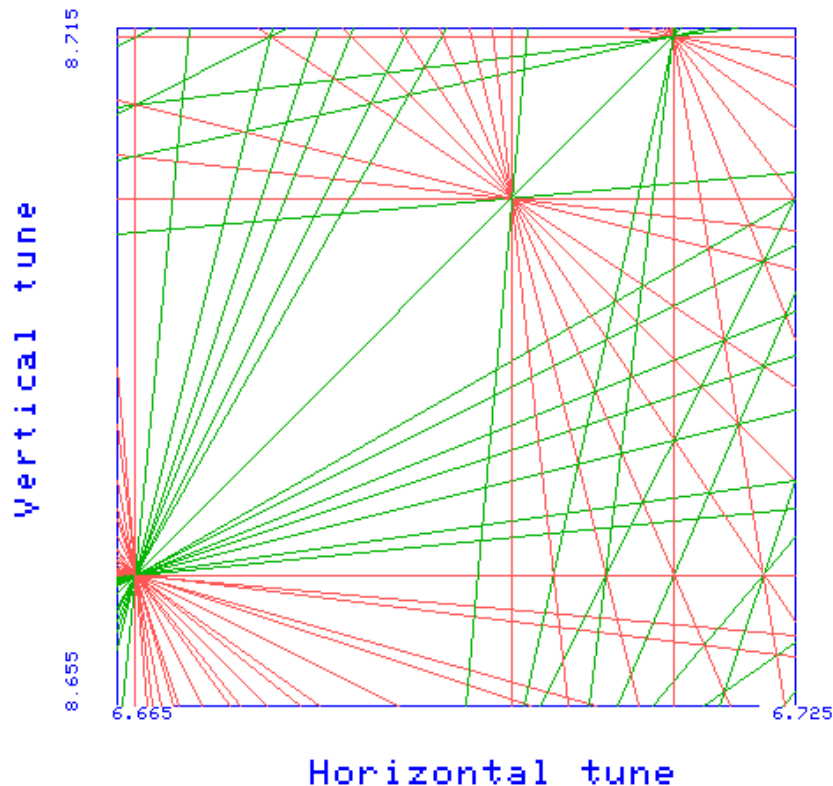
0.0 $\mu\text{W/Hz}$ at $80\text{E}+10$ pbars





Betatron Tunes

- The betatron tunes were increased from the Run I values of 6.608H x 8.611V to 6.695H x 8.685V in Run II to reduce the beta functions of the Accumulator Lattice Upgrade.
- The tunes are kept split apart by 0.010 for the Schottky emittance monitors to work properly.
 - Moving the tunes to within 0.003 of each other will cause the planes to couple
- Setting the tunes on relatively high order resonances (>12) will cause noticeable changes in lifetime but rarely changes the emittance growth rate significantly.



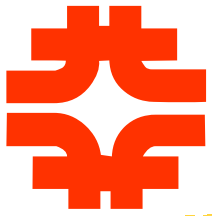
Resonance Lines from order 1 through 12

Operating tune is in the center of the diagram



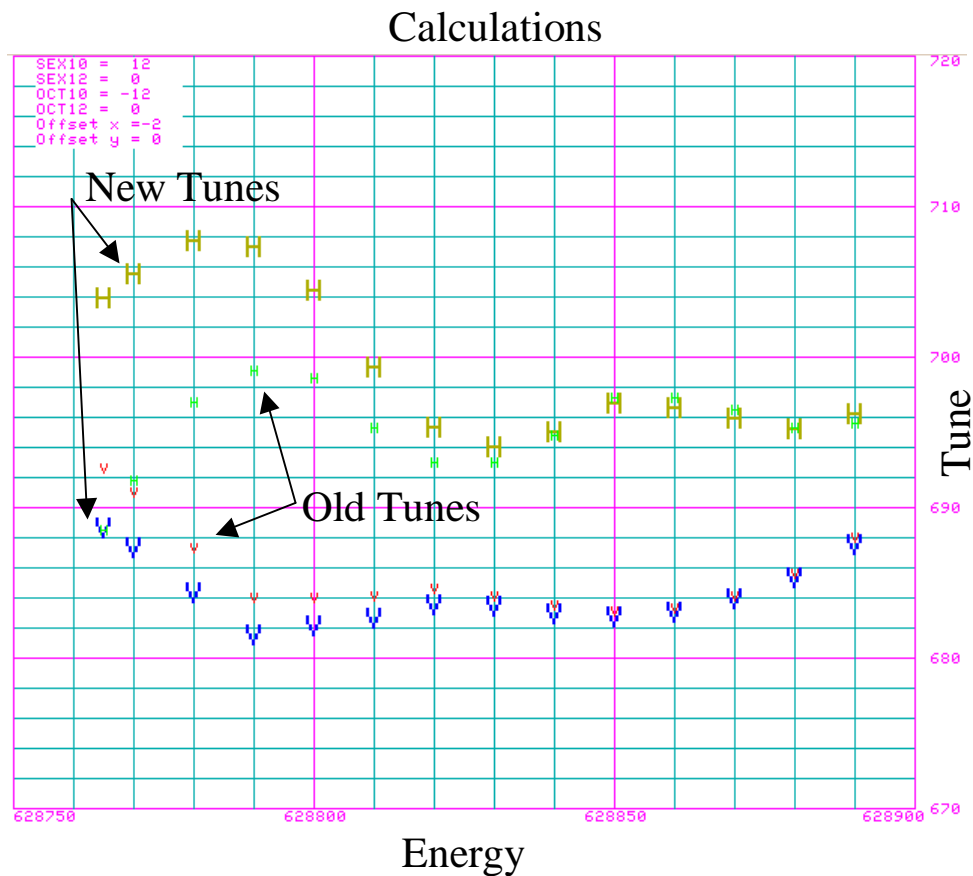
Betatron Tunes Across the Momentum Aperture

- The momentum aperture of the Accumulator is 1.6%
 - The core is stored on the low energy edge of the aperture
 - The beam is extracted on the high energy edge of the aperture.
- If the planes couple when the beam is being extracted from the core
 - The sum of the horizontal and vertical emittance tends to be preserved
 - The product of the emittances grow significantly (> 50%)
 - The horizontal emittance of the core is much greater than the vertical emittance because of the horizontal heating.
- The betatron tunes across the momentum aperture are controlled with a family of sextupoles and octupoles
- There are families of skew quadrupoles and skew sextupoles for correcting the coupling across the momentum aperture.

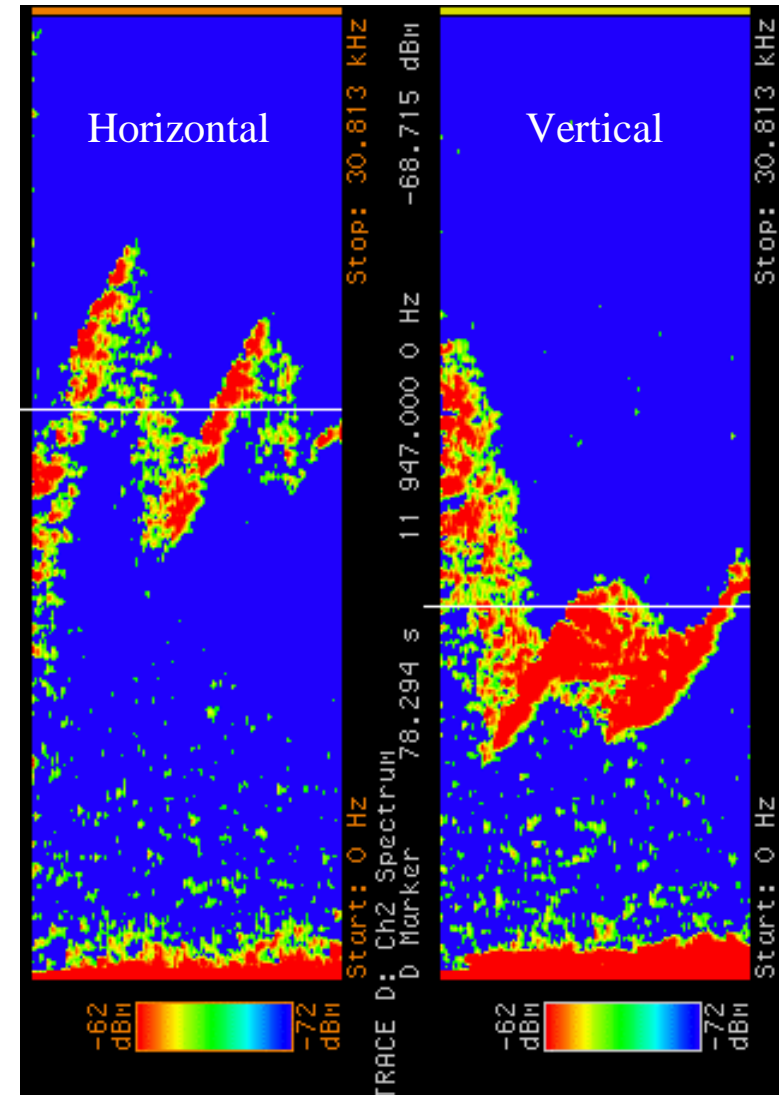


Betatron Tunes Across the Momentum Aperture

- The tunes have been adjusted across the aperture to minimize coupling



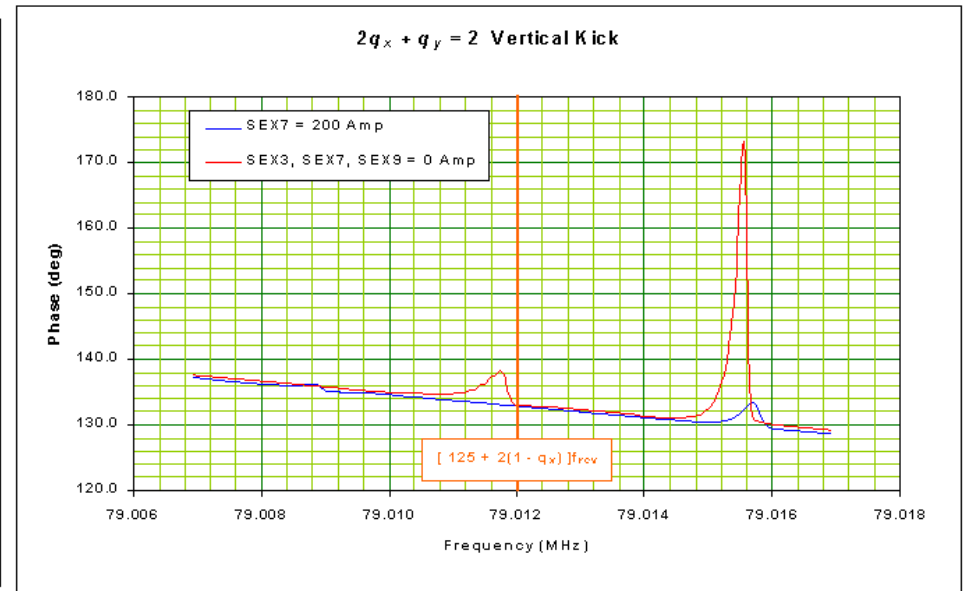
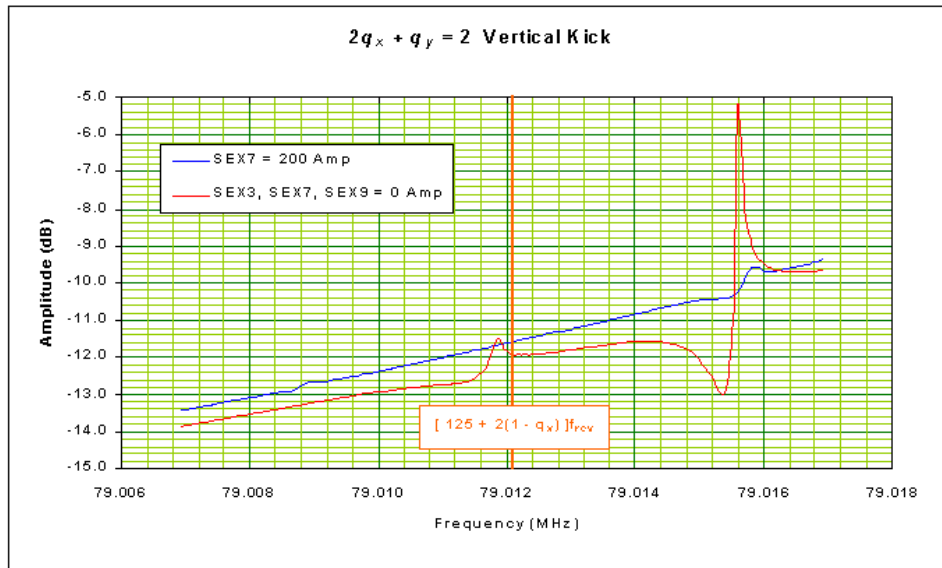
Measured Tune scan with old tune profile

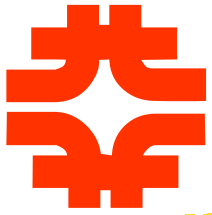




3rd Order Harmonic Correction

- The Accumulator has three families of sextupoles to for harmonic correction of the 2/3 resonance
- The harmonic correction sextupoles are adjusted with beam transfer functions at the the betatron resonance lines.
- Adjustment of the harmonic correction has not improved emittance growth

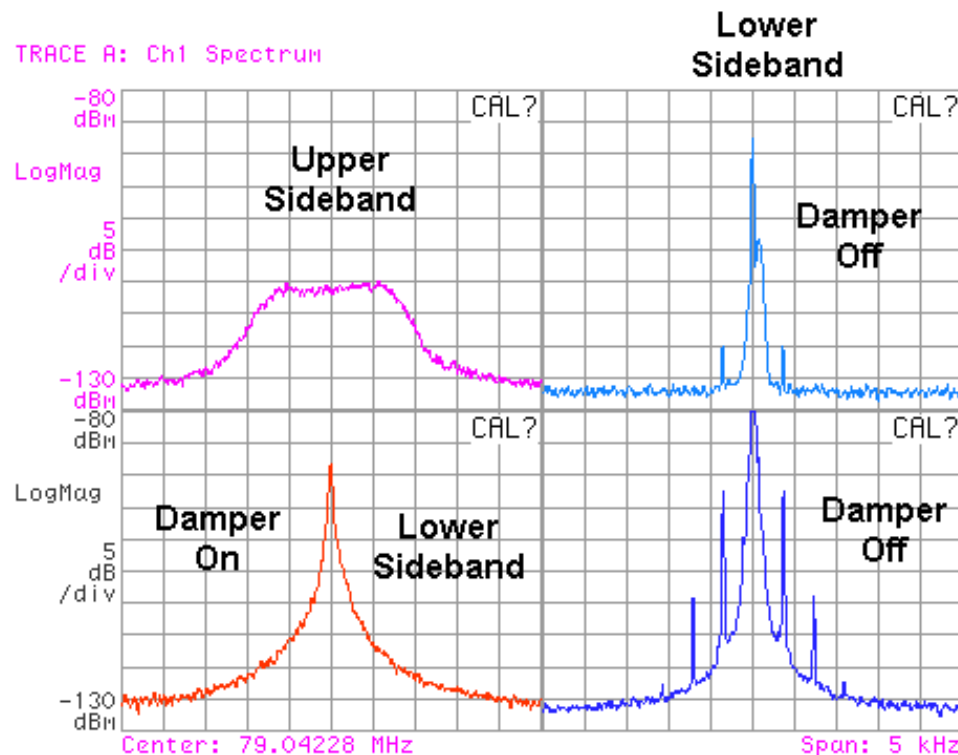




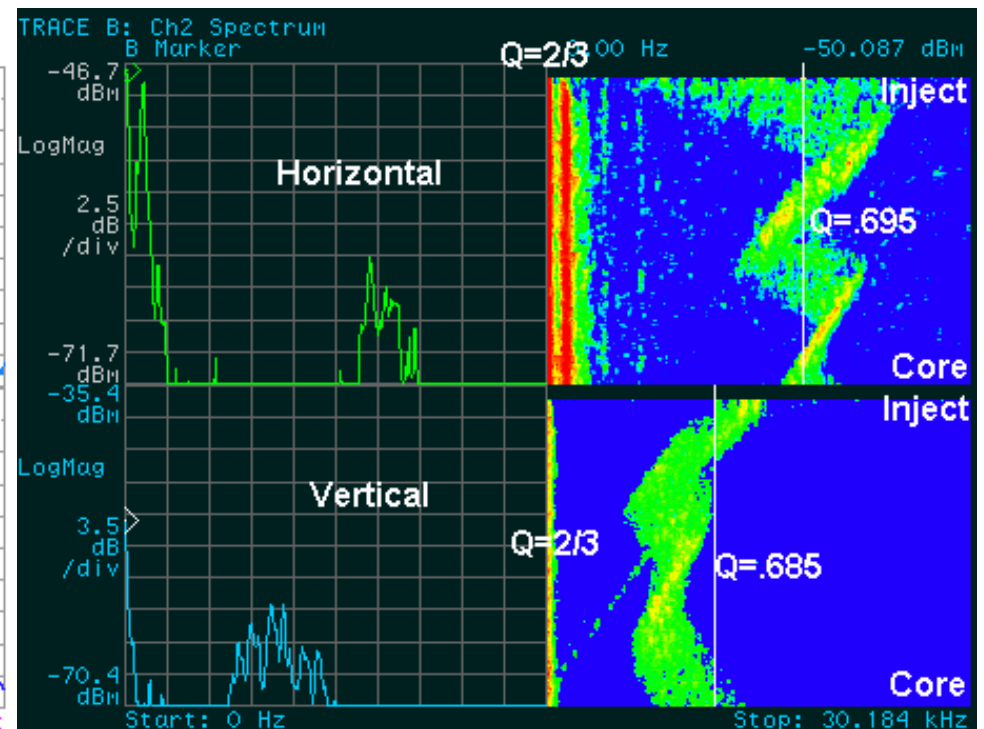
Instabilities

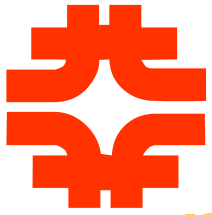
- Core beam on the edge of stability because of the negative local vertical chromaticity at the core.
 - There is not enough strength in the octupoles to correct the core vertical chromaticity
- Bringing the entire stack to the central orbit where the vertical chromaticity is good and allows the dampers to be turned off did not change the emittance growth rate.

Accumulator Core Vertical Schottky Spectrum



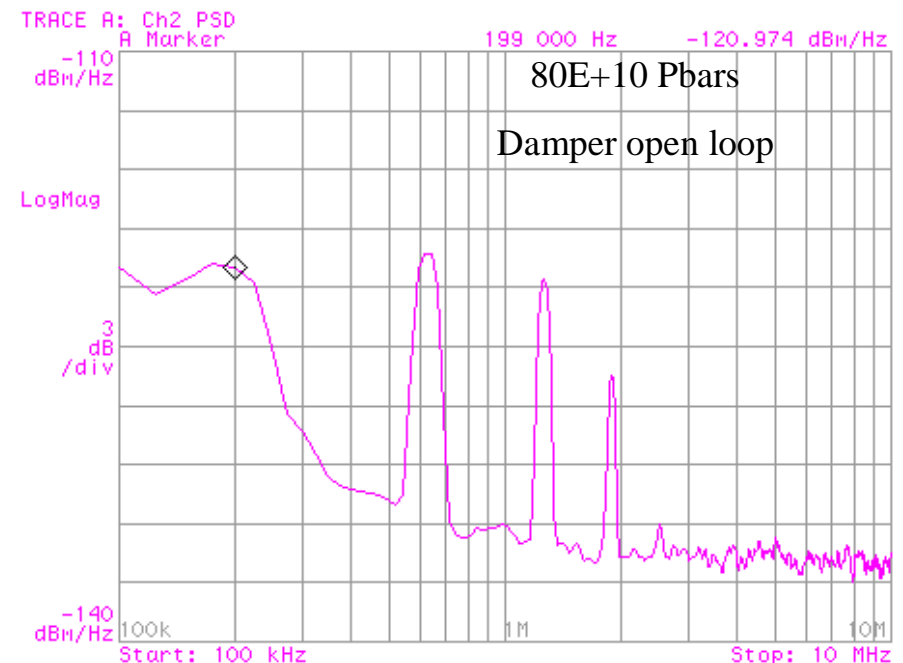
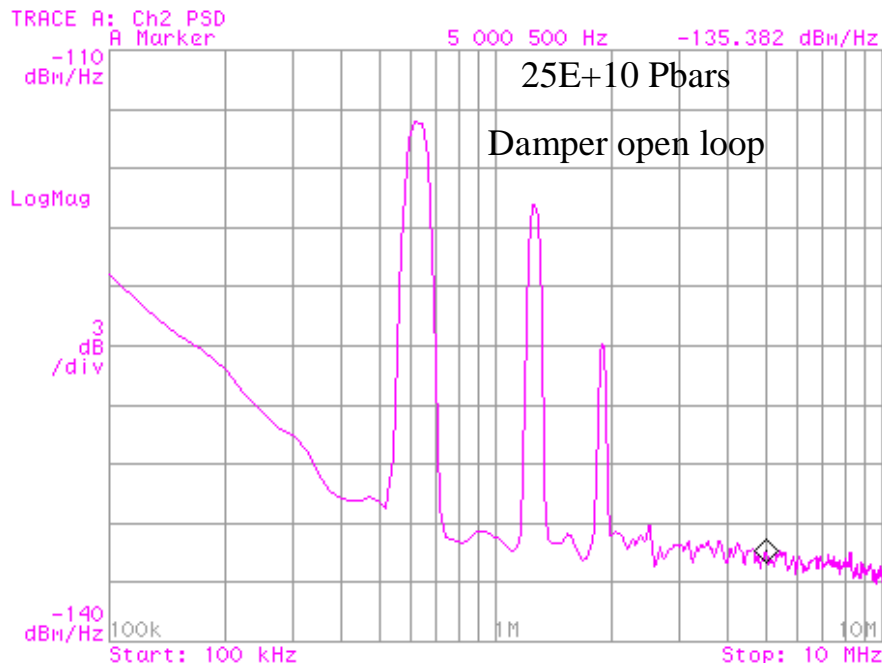
Tune across Accumulator Momentum Aperture





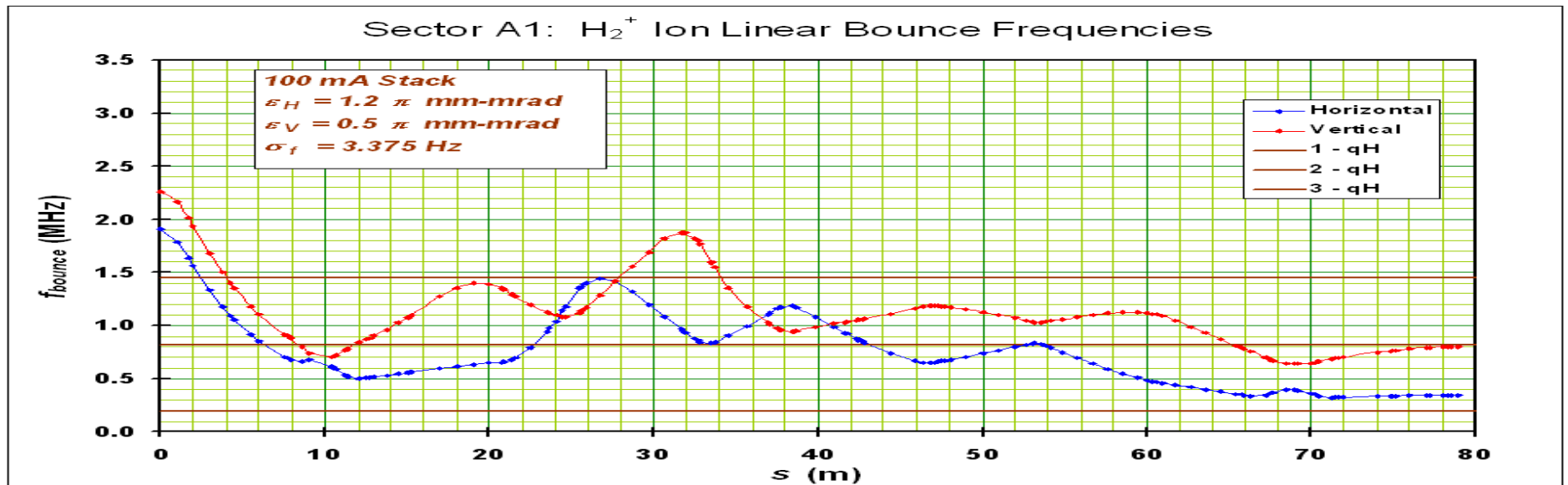
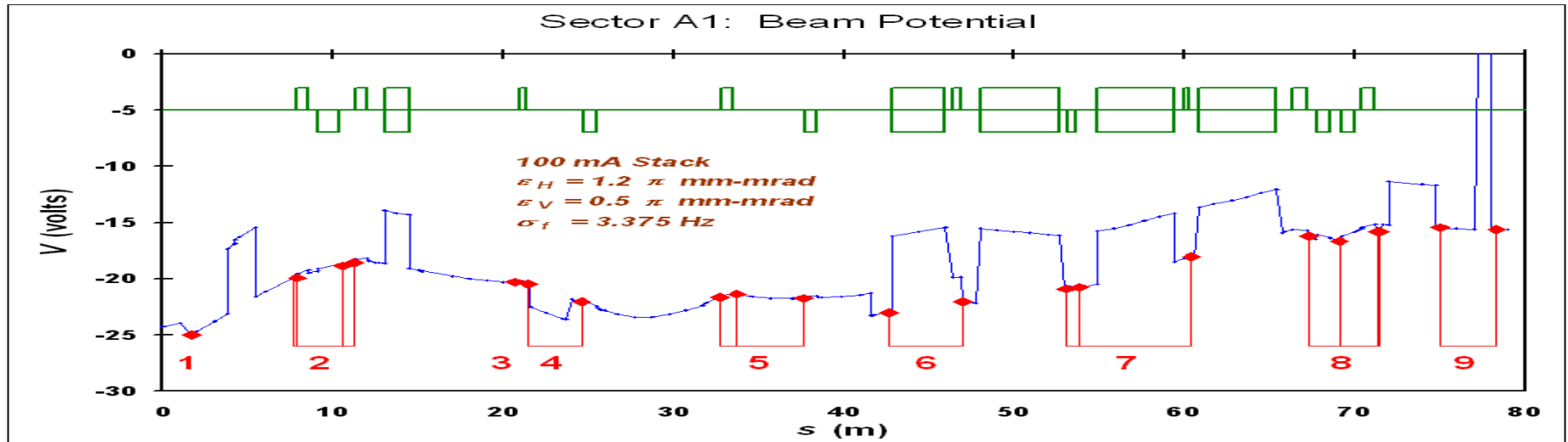
Ions

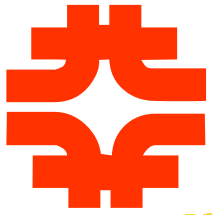
- There are trapped ions in the pbar beam.
 - A clearing voltage system at 1 kV is distributed around the ring.
 - At $100\text{E}+10$ pbars, if the clearing voltage is reduced to below 200V, ion instabilities and rapid emittance growth is observed.
 - An 20V $h=1$ square wave stabilizing RF system is applied to the beam.
 - Stacking rates drop for stacks above $20\text{E}+10$ pbars if the stabilizing RF is turned off.
 - At larger stacks, large emittance growth is observed if the stabilizing RF is turned off.
 - Increasing the stabilizing RF voltage above 20V does not change the emittance growth rate.
- At stack sizes $> 50\text{E}+10$ pbars, the 1-Q line is observed on the horizontal damper system





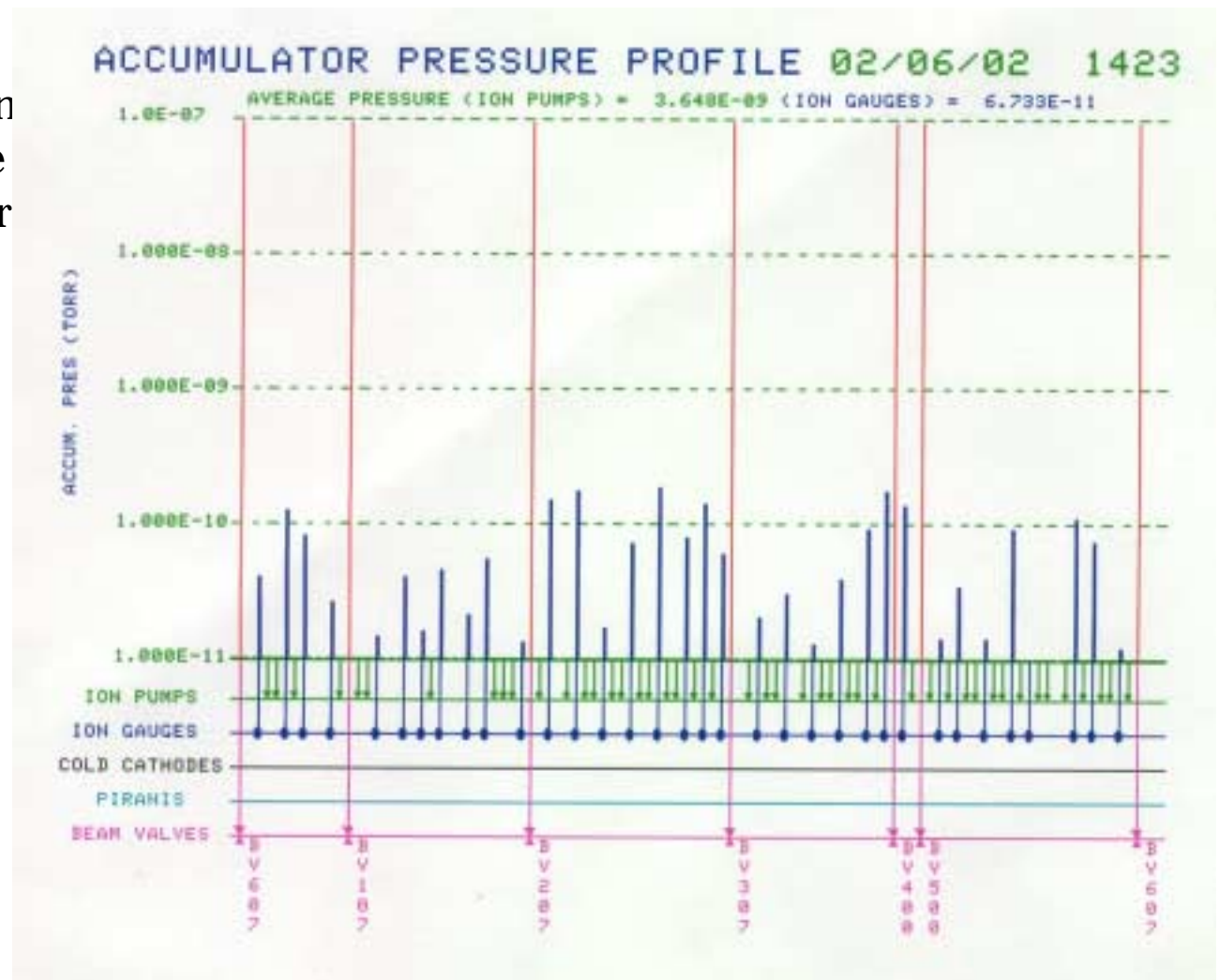
Ions

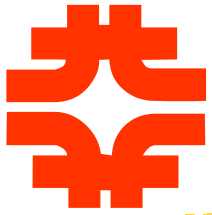




Vacuum

- After the liquid nitrogen leak was repaired in the A60 sector in November '01, the vacuum in the Accumulator is comparable to the best vacuum conditions in Run I



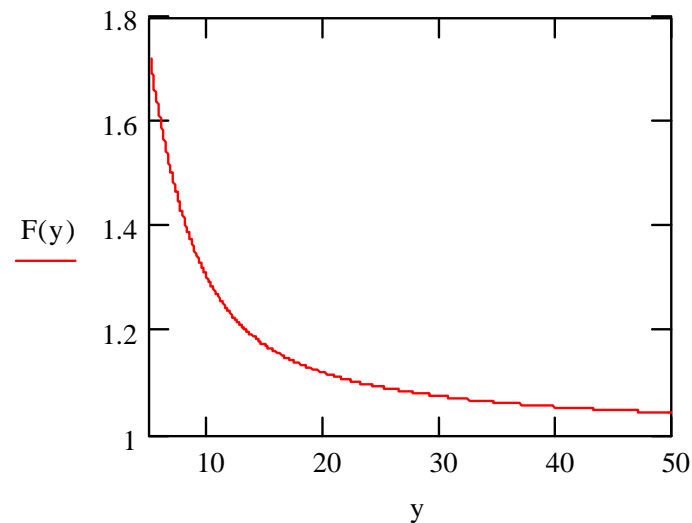


Scattering on the Residual Gas

- Beam lifetime due to scattering on the residual gas

$$\tau_{scat}^{-1} = \frac{2\pi c r_p^2}{\gamma^2 \beta^3} \left(\sum_i n_i Z_i^2 \left(\frac{\overline{\beta}_x}{\varepsilon_{mx}} F\left(\frac{\varepsilon_{mx}}{2\varepsilon_x}\right) + \frac{\overline{\beta}_y}{\varepsilon_{my}} F\left(\frac{\varepsilon_{my}}{2\varepsilon_y}\right) \right) + \sum_i n_i \sigma_i c \beta \right)$$

$$\overline{\beta}_{x,y} = \frac{1}{C} \int \beta_{x,y} ds$$



- Total beam lime time measured with low intensity protons ~1400 hour
- Coulomb scattering ~2800 hour
- Nuclear absorption ~2700 hour



Scattering on the Residual Gas

- Emittance growth rate is closely related to the beam life time

$$\frac{d\epsilon_{x,y}}{dt} = \frac{2\pi c r_p^2}{\gamma^2 \beta^3} \left(\sum_i n_i Z_i^2 \right) \overline{\beta_{x,y}}$$

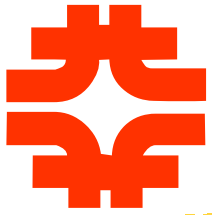
- Presuming that the relative gas composition is proportional to a single point measurement performed 2 years ago we obtain the vacuum and the emittance growth rates

$$\frac{d\epsilon_x}{dt} = 0.088 \text{ mm mrad/hour}$$

$$\frac{d\epsilon_y}{dt} = 0.052 \text{ mm mrad/hour}$$

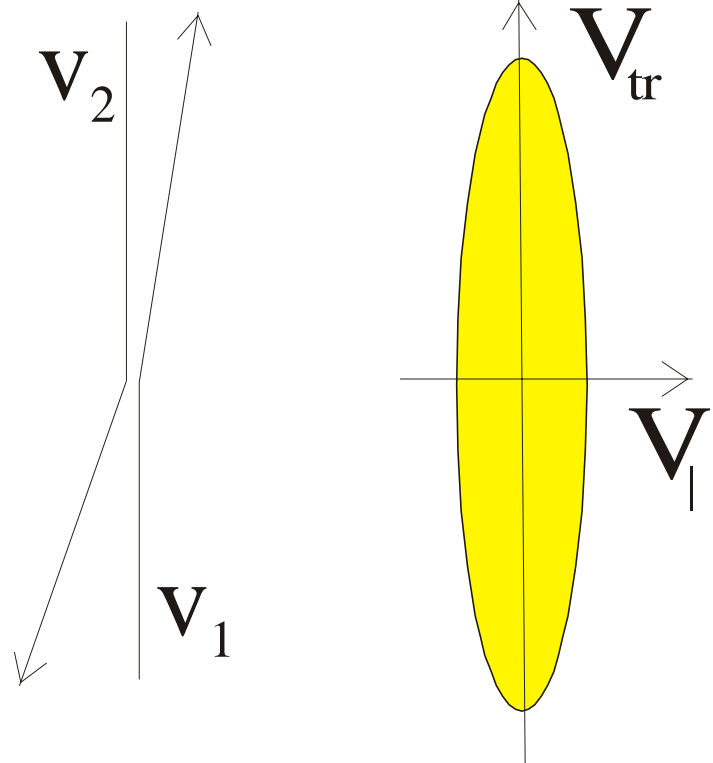
$$P = \begin{pmatrix} 3.36 \times 10^{-10} \\ 4.32 \times 10^{-10} \\ 1.44 \times 10^{-11} \\ 7.2 \times 10^{-12} \\ 6 \times 10^{-12} \\ 1.2 \times 10^{-11} \\ 7.2 \times 10^{-12} \\ 9.6 \times 10^{-12} \end{pmatrix} \begin{pmatrix} \text{H} \\ \text{H}_2 \\ \text{CO} \\ \text{N}_2 \\ \text{C}_2\text{H}_2 \\ \text{C}\cdot\text{H}_4 \\ \text{CO}_2 \\ \text{Ar} \end{pmatrix} \quad [\text{Torr}]$$

- Measured minimum **vertical emittance growth** time coincides well with the calculations
- The **horizontal growth** is usually above predictions and grows fast with beam current



Intra-beam Scattering

- If in the beam frame the longitudinal momentum spread is much less than the transverse one the IBS formulas can be significantly simplified





IBS Growth Rate for Longitudinal Degree of Freedom

- IBS transfers the energy from the transverse degrees of freedom to the longitudinal one and the growth rate can be approximated by the following formula:

$$\frac{d}{dt}(\theta_{\parallel}^2) \equiv \frac{d}{dt}\left(\frac{p_{\parallel}^2}{p}\right) = \sqrt{\frac{\pi}{2}} \frac{e^4 N L_C}{m_p^2 c^3 \gamma^3 \beta^3 C} \left\langle \frac{\Xi_{\parallel}(\theta_x, \theta_y)}{\sigma_x \sigma_y \sqrt{\theta_x^2 + \theta_y^2}} \right\rangle_s$$

where averaging is performed along the beam orbit

$$\Xi_{\parallel}(x, y) \approx 1 + \frac{\sqrt{2}}{\pi} \ln\left(\frac{x^2 + y^2}{2xy}\right) - 0.055 \left(\frac{x^2 - y^2}{x^2 + y^2}\right)^2$$

L_c - is the Coulomb logarithm,

C - is the ring circumference,

- The beam sizes and local angular spreads along the ring are determined by

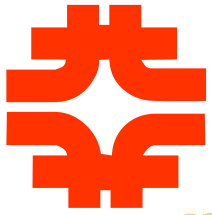
$$\sigma_x = \sqrt{\varepsilon_x \beta_x + D^2 \theta_{\parallel}^2}$$

$$\sigma_y = \sqrt{\varepsilon_y \beta_y}$$

$$\theta_x = \sqrt{\frac{\varepsilon_x}{\beta_x} \left(1 + \frac{(D' \beta_x + \alpha_x D_x)^2 \theta_{\parallel}^2}{\varepsilon_x \beta_x + D^2 \theta_{\parallel}^2} \right)}$$

$$\theta_y = \sqrt{\varepsilon_y / \beta_y}$$

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}$$



The IBS Growth Rate for Transverse Degree of Freedom

- The heating of the longitudinal degree of freedom causes cooling for both transverse degrees of freedom.
- Additional mechanism heats the horizontal degree of freedom
 - At regions with non-zero dispersion, changes in the longitudinal momentum change the particles reference orbits, which additionally excites the horizontal betatron motion

$$\frac{d\varepsilon_x}{dt} = \frac{1}{2} \left\langle A_x \frac{d\theta_{\parallel}^2}{dt} \right\rangle_s \quad \text{where} \quad A_x = \frac{D^2 + (D'\beta_x + \alpha_x D)^2}{\beta_x}$$

Coefficient 1/2 is related to the fact that the beam is unbunched

- Finally, one can write for the emittance growth rates

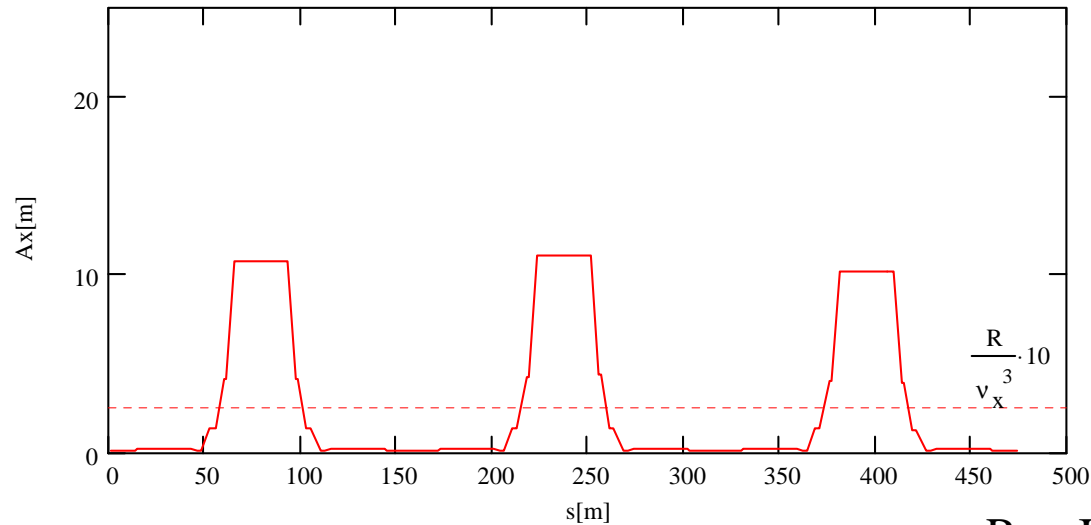
$$\frac{d\varepsilon_{x,y}}{dt} = \frac{\sqrt{2\pi}e^4 N L_C}{8m_p^2 c^3 \gamma^3 \beta^3 C} \left\langle \frac{1}{\sigma_x \sigma_y \sqrt{\theta_x^2 + \theta_y^2}} \left[2A_x \Xi_{\parallel}(\theta_x, \theta_y) - \frac{\beta_x}{\gamma^2} \Xi_{\perp}(\theta_x, \theta_y) - \frac{\beta_y}{\gamma^2} \Xi_{\perp}(\theta_y, \theta_x) \right] \right\rangle_s$$

where

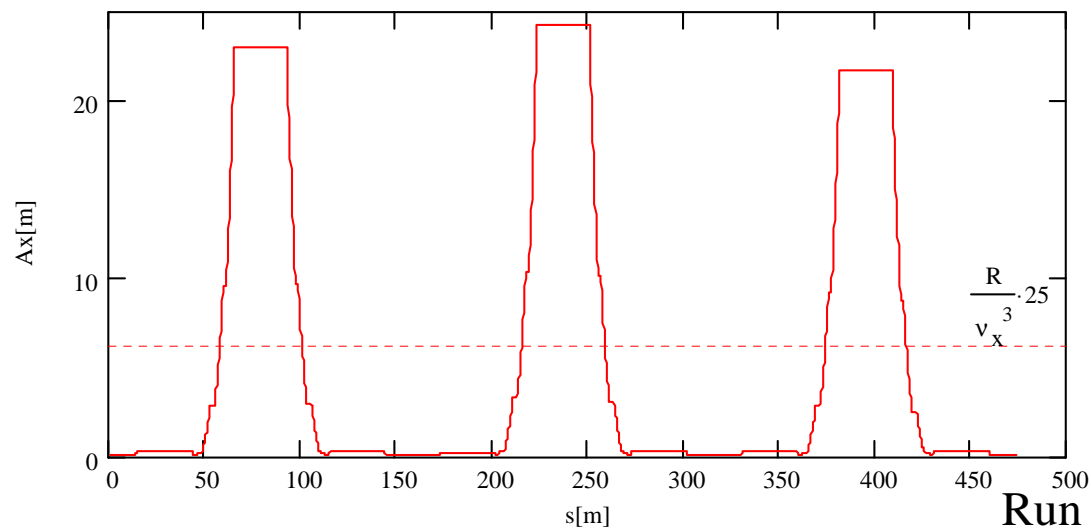
$$\Xi_{\perp}(x, y) \approx 1 + \frac{2\sqrt{2}}{\pi} \ln \left(\frac{\sqrt{3x^2 + y^2}}{2y^2} x \right) + \frac{0.5429 \ln(y/x)}{\sqrt{1 + \ln^2(y/x)}}$$



Comparison of the Run I and Run II Accumulator Lattices

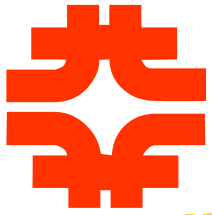


Run I Lattice



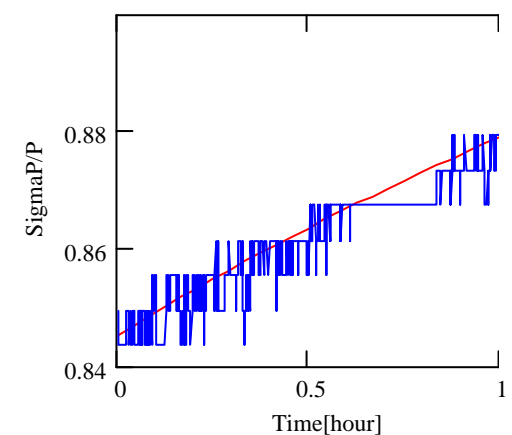
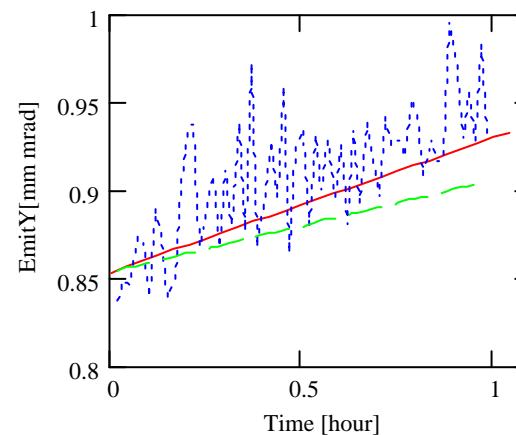
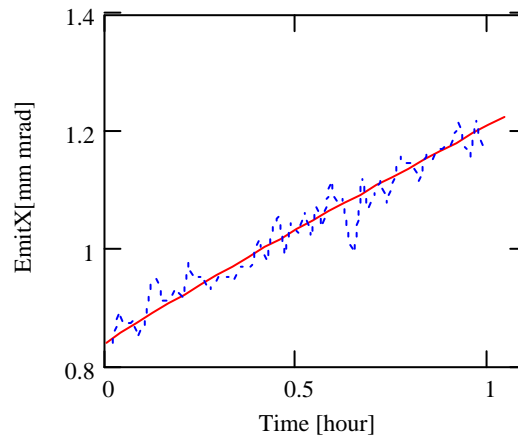
Run II Lattice

- Both lattices are not designed to have small IBS
- Run II lattice amplifies IBS by more than factor of two in comparison with the Run I lattice.

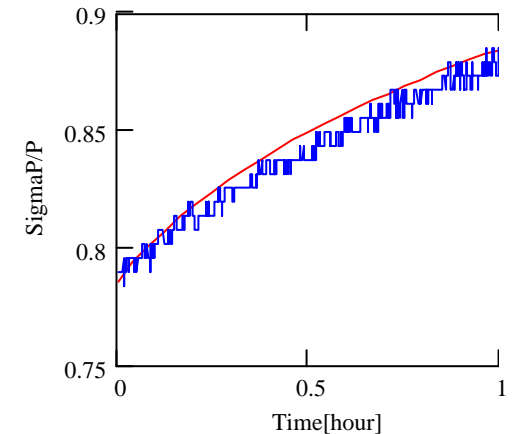
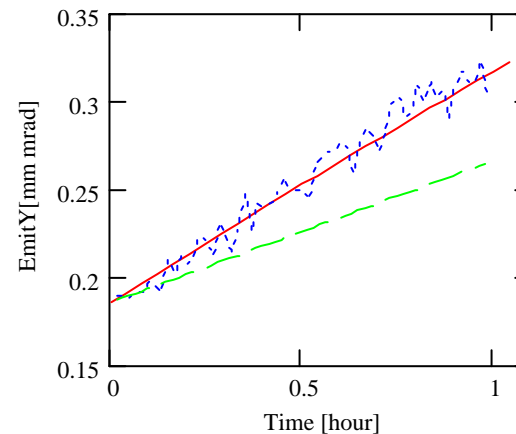
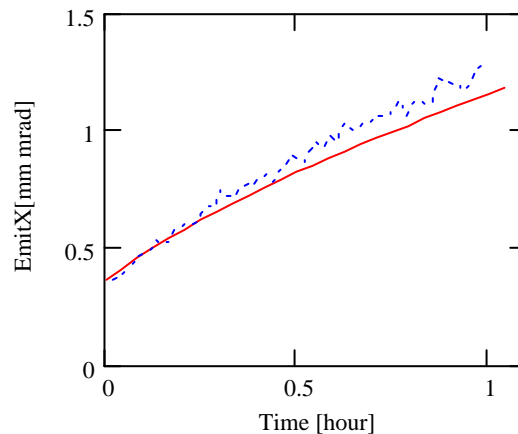


Comparison with Experiment

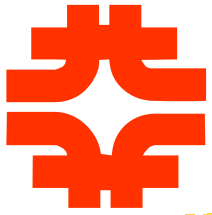
Protons, $I_{\text{beam}} = 13.5$ mA, Lifetime = 1400 hour, beam is scraped from 100 mA, Apr.30.02



Antiprotons, $I_{\text{beam}} = 12.1$ mA, Lifetime = 900 hour, beam is scraped from 24 mA, Apr.30.02

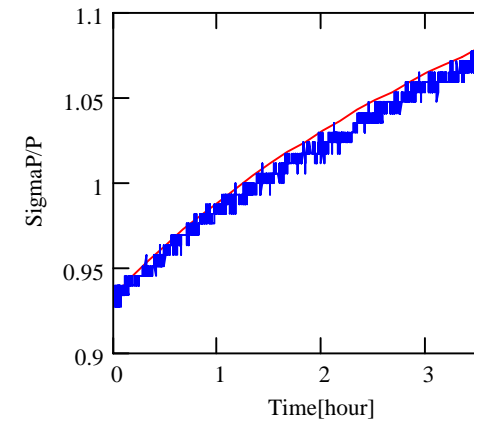
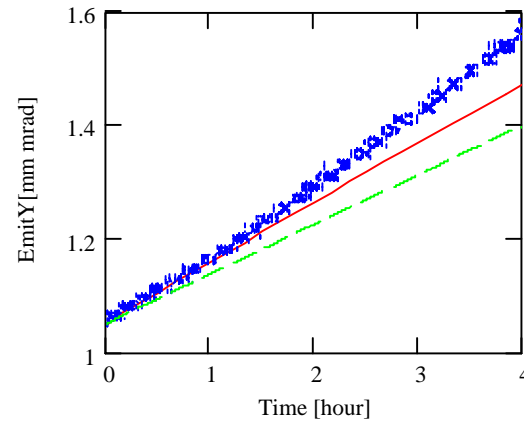
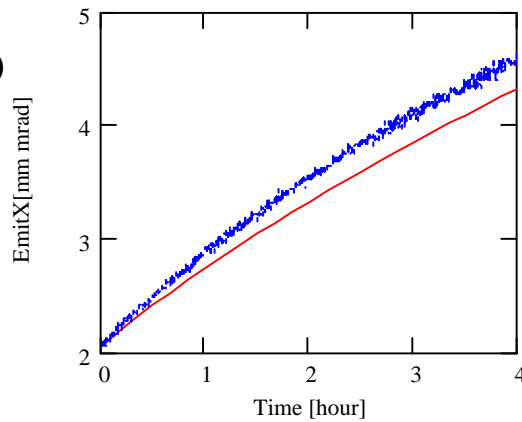


- Green line shows the emittance growth from the gas scattering only
- X-Y coupling causes additional growth for vertical emittance, $\kappa = 0.04$
- Beam scraping makes distribution non-Gaussian. It affects the growth rates but we do not have a clear answer how much

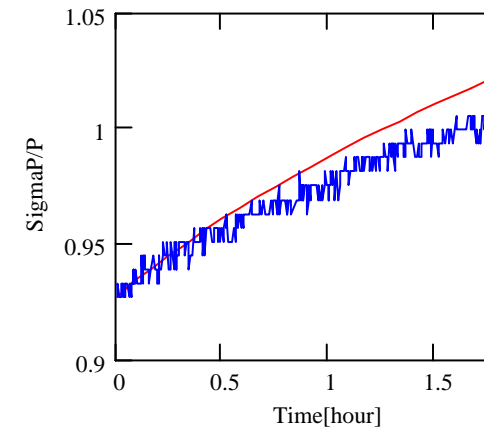
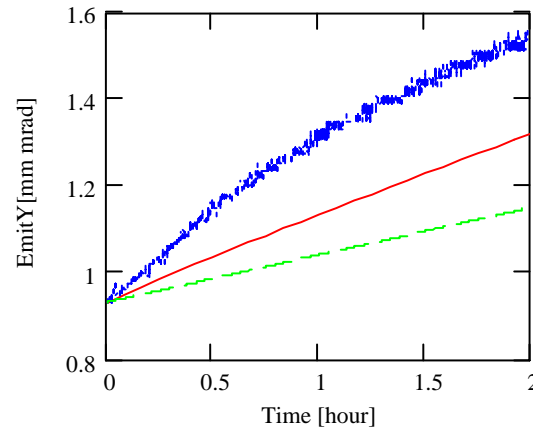
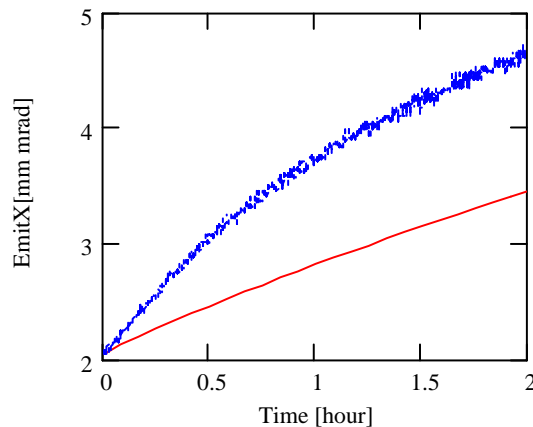


Comparison with Experiment

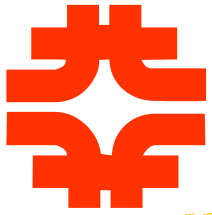
Protons, $I_{\text{beam}}=48.2$
mA, Lifetime = 800
hour, Mar.26.02



Antiprotons,
 $I_{\text{beam}}=50.8$ mA,
Lifetime = 650
hour, Mar.27.02



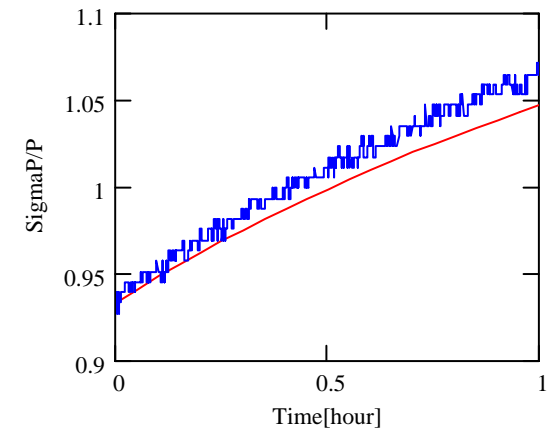
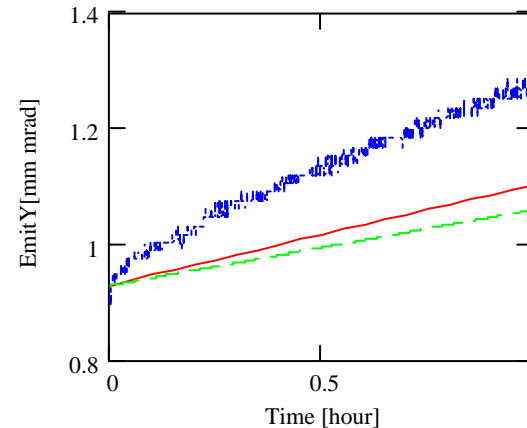
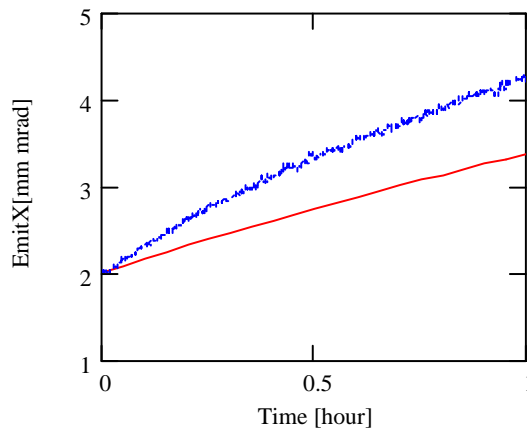
- Green line shows the emittance growth from the gas scattering only
- X-Y coupling causes additional growth for vertical emittance, $\kappa = 0.04$
- Presence of ions in the antiproton beam causes decrease of beam lifetime due to worsening of the effective vacuum and drives additional emittance growth due to ion instability



Comparison with Experiment

Antiprotons,

$I_{\text{beam}} = 100 \text{ mA}$,
Lifetime = 550
hour,
Mar.27.02



Remarks about measurements and theory

- Both IBS and residual scattering are taken into account in the theoretical model
 - Both models have logarithmic accuracy with expected accuracy of about 10%
- IBS theoretical model is build for the Gaussian distribution function
 - It is not quite accurate for the proton beam and not always true for the antiproton beam
 - That brings additional uncertainty but it is difficult to say how much
- Longitudinal momentum spread for all presented date sets was fudged by factor of 1.15 to get coincidence between theory and measurements for the momentum spread growth rate.
 - Momentum spreads reported by A:SIGMAP and A:FRWDTH is different by ~40% and the are not always proportional to each other in the both cases of proton and antiproton beams
 - We need to investigate the reason of this discrepancies

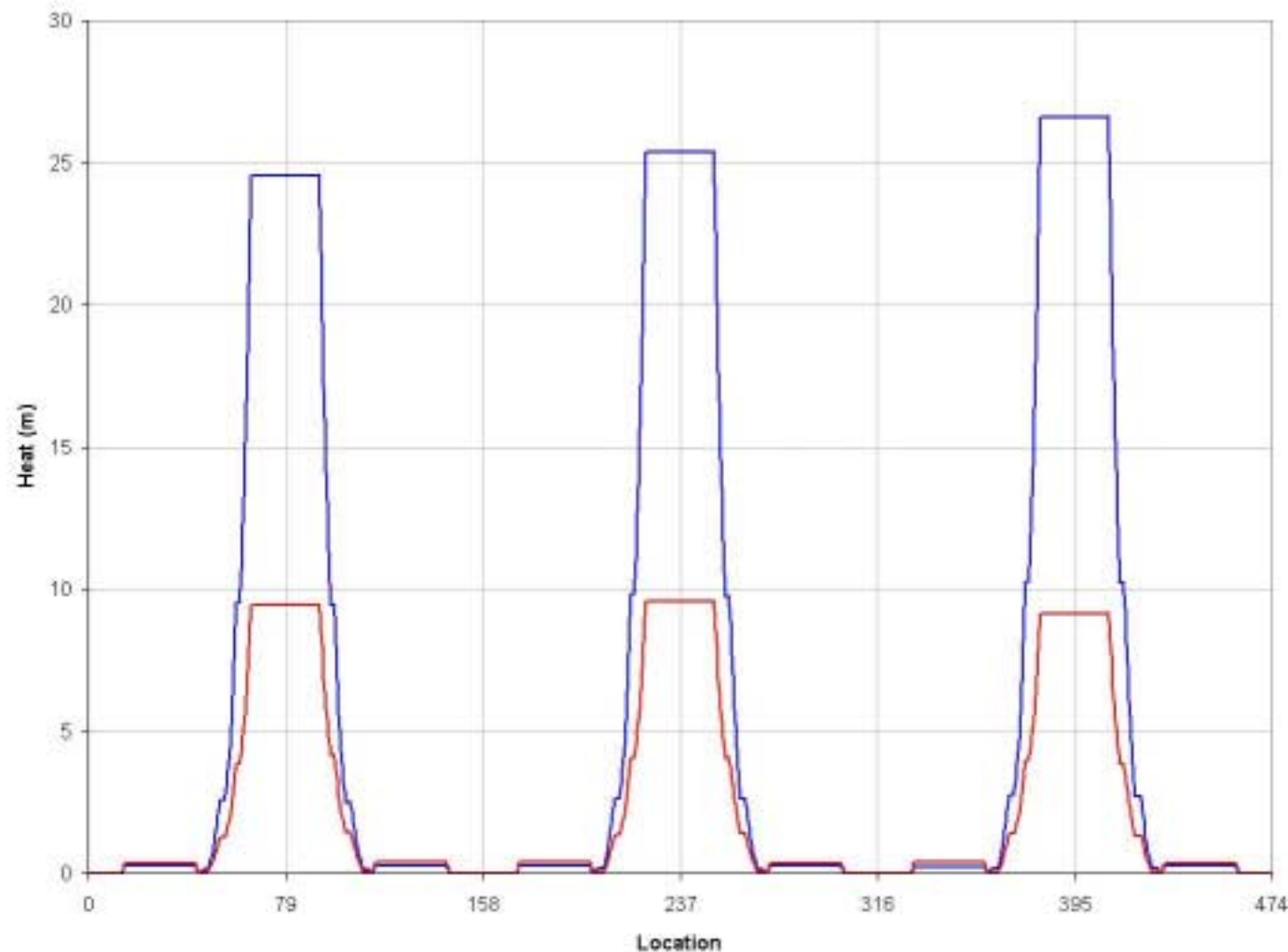


Accumulator IBS Lattice Studies

- An Accumulator lattice with a much smaller IBS heating term was designed.
- The lattice was designed with the following constraints
 - No hardware changes to the present quadrupole configuration.
 - Same betatron tunes as the present Run II lattice
 - Zero dispersion in the odd straight sectors
 - High dispersion in the even straight sectors
 - Correct betatron cooling phase advances
 - Correct kicker phase advances
 - $\gamma_t > 5.5$ ($\eta < 0.022$)



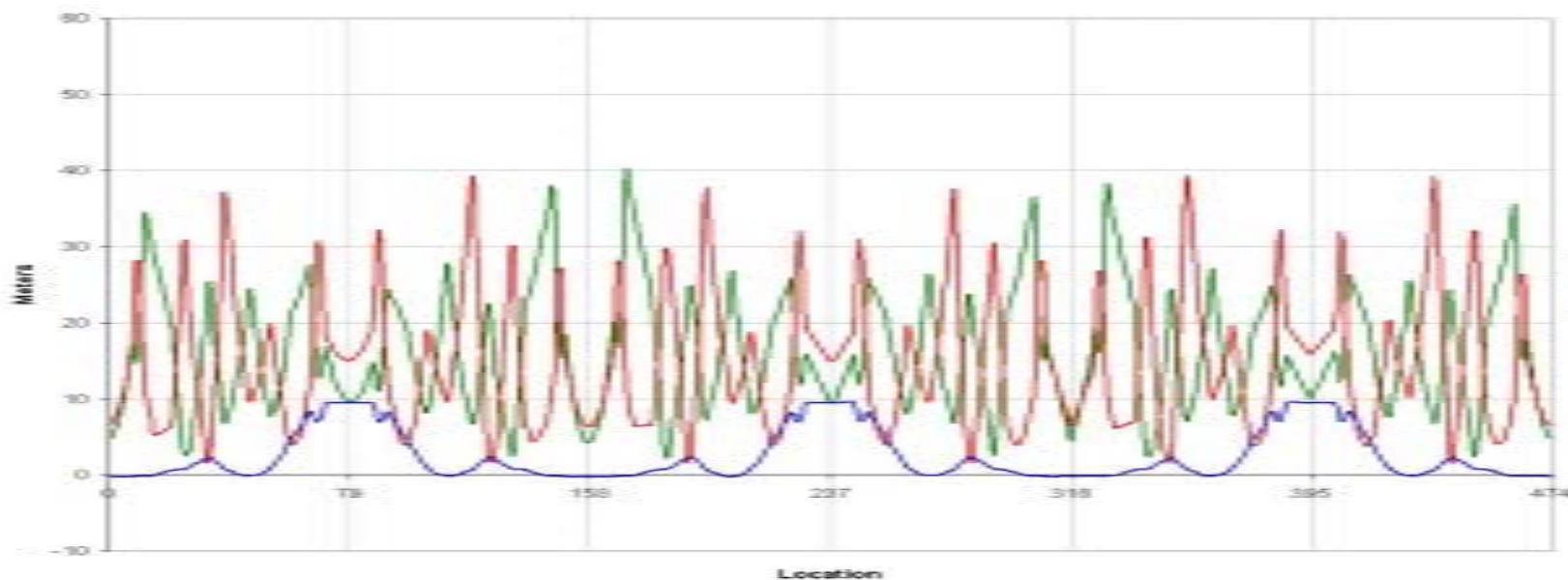
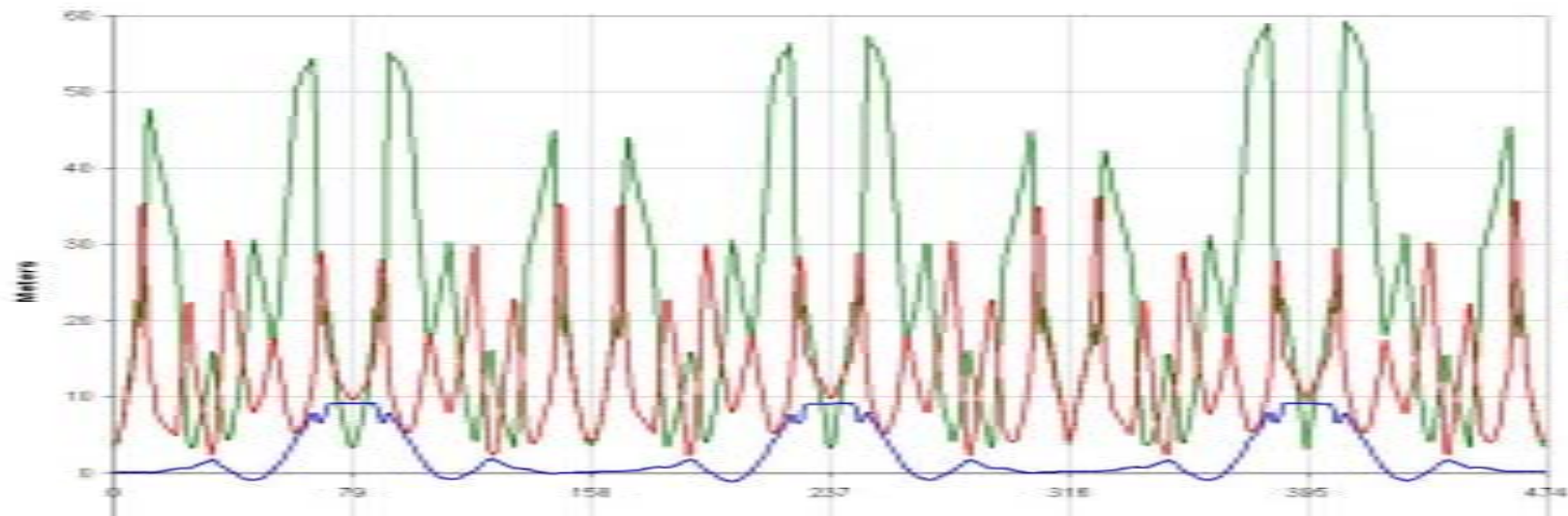
Accumulator Lattice IBS Heating Term



$$\frac{D^2 + (\beta D' + \alpha D)^2}{\beta}$$

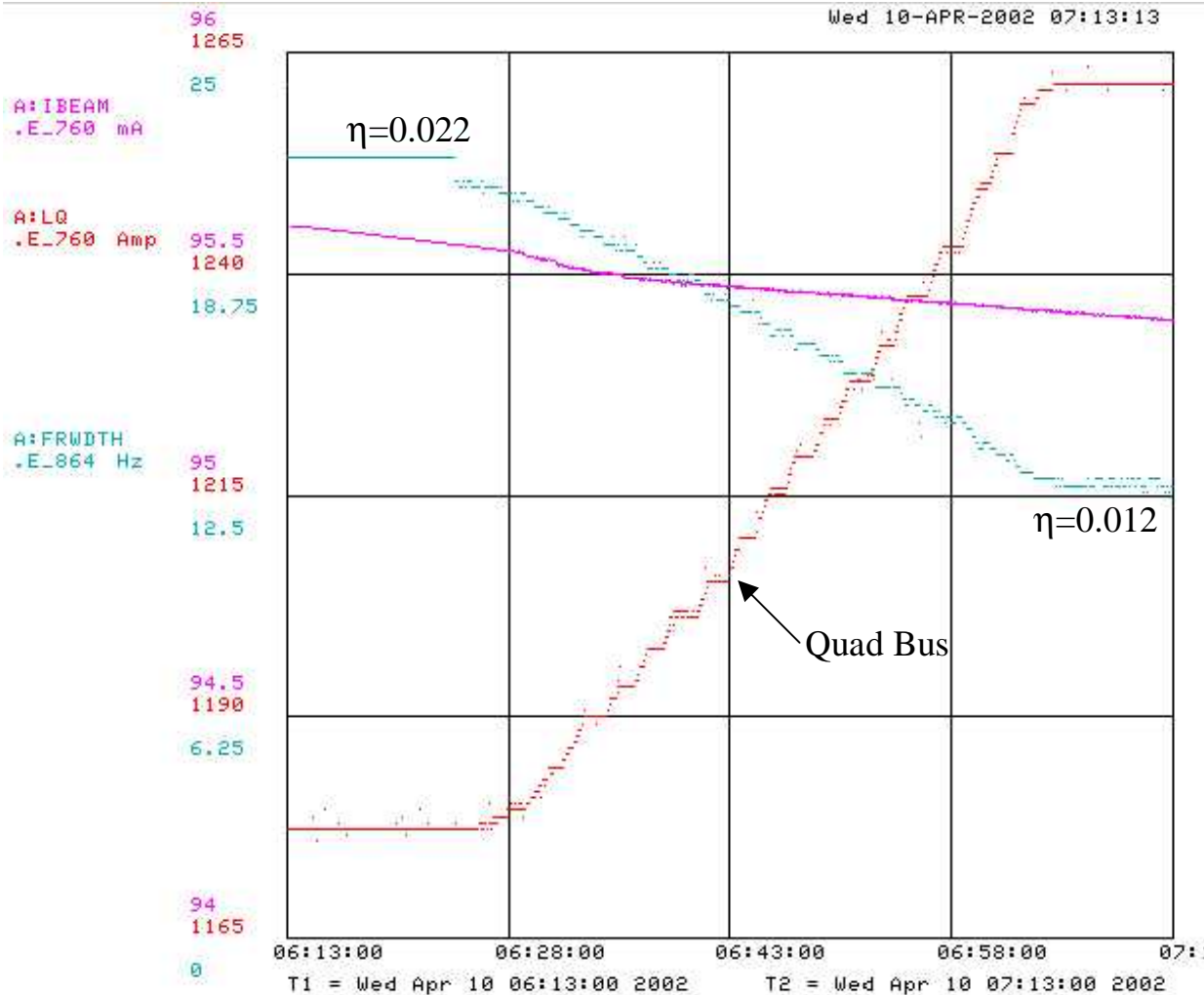


Accumulator Lattices





Ramping the Lattice



- With about 96×10^{10} pbars stored in the stack, the Accumulator was ramped between lattices with less than 0.3% beam loss

Lattice ramping back from new lattice to present Run II lattice



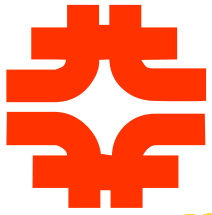
Lattice Ramping Procedure

1. Cool beam on Core. Use Thermostat. Frequency width should be 13.5.
2. Set A:RLLFS1 to A:CENFRQ. Unshort ARF3. Turn on DAC and High Level. Turn ARF3 to get about 10-20Volts.
3. Turn off 4-8 GHz Momentum cooling. Add 50 ps to trunk trombone of 4-8 Momentum system. Move plates to central orbit. Setup microwave spectrum analyzer to a harmonic of 628,848.
4. Turn off all transverse cooling
5. Bunch beam on ARF3 to 2300V (DAC 9.3). Move beam to 628848.
6. Debunch beam. Turn off ARF3. Short the gap.
7. Add 33 ps on to core settings for all transverse systems.
8. Turn on all cooling slowly (including the 4-8 Momentum)
9. Check and Adjust Signal suppression.
10. Use the Thermostat mode that DOES NOT MOVE the 4-8 Arrays.
11. Adjust chromaticity.
12. Adjust tunes – keep tunes spread by 0.010
13. Change 300 MHz Lo's
14. Adjust coupling.
15. Turn off Thermostat. Measure eta with ARF3. Turn off ARF3 when done and short the gap.
16. Set A:RCETA to measured value
17. Get frequency width to 13.5 Hz with Thermostat. Use the Thermostat mode that DOES NOT MOVE the 4-8 Arrays.
18. Reset Data logger. Make sure data logger is working.
19. Turn off Thermostat. Turn off all cooling.
20. Heat beam for 1 hour
21. Cool beam. Use Thermostat.
22. Turn off Thermostat. Reduce momentum cooling gain.
23. Change Lattice
24. Adjust tunes – keep tunes spread by 0.010
25. Change 300 MHz Lo's

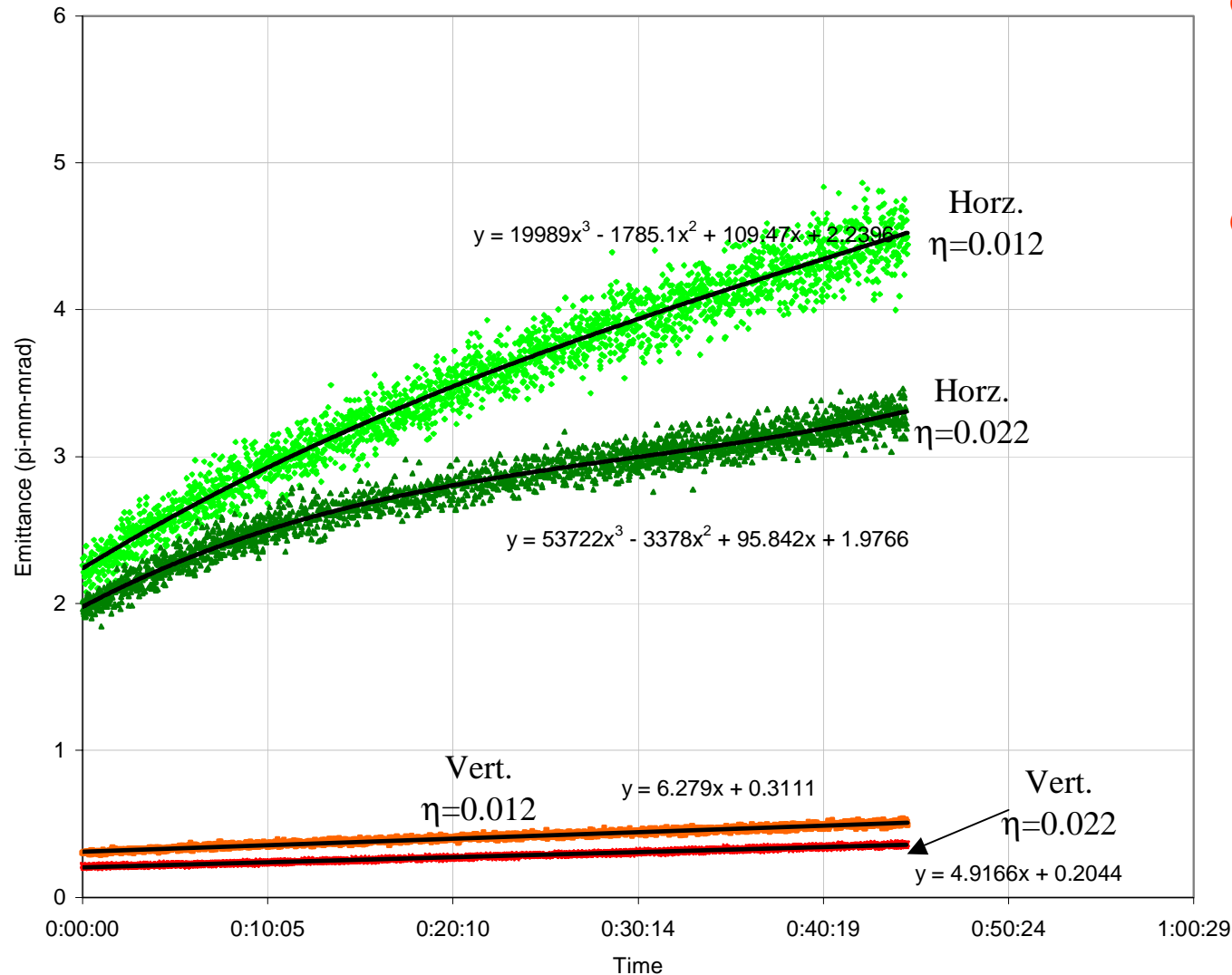


Lattice Ramping Procedure

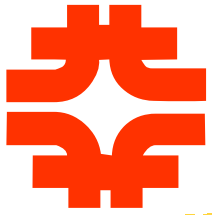
26. Adjust coupling.
27. Turn off Thermostat. Measure eta with ARF3. Turn off ARF3 when done and short the gap.
28. Set A:RCETA to measured value
29. Get frequency width to $(\text{ETA}_{\text{new}} / \text{ETA}_{\text{old}}) \times 13.5$ Hz with Thermostat. Use the Thermostat mode that DOES NOT MOVE the 4-8 Arrays.
30. Check and Adjust Signal suppression.
31. Cool beam to smallest emittance and record value.
32. Turn off all transverse cooling systems.
33. Mis-phase 4-8 GHz transverse cooling systems by adding or subtracting 125 ps to trunk trombones.
34. Back off on 4-8 transverse gain and turn on 4-8 GHz transverse cooling systems.
35. Slowly heat the beam until $\text{horz_emit_new_start} = (12.5/13.2) \times \text{horz_emit_old_start}$ and $\text{vert_emit_new_start} = (13.4/16.1) \times \text{vert_emit_old_start}$
36. Turn off Thermostat. Turn off all cooling.
37. Heat beam for 1 hour
38. Remove 125ps delay change so that transverse cooling systems will cool.
39. Cool beam. Use Thermostat.
40. Turn off Thermostat. Reduce momentum cooling gain.
41. Change Lattice back to old lattice
42. IMPORTANT!!!! Remove Chromaticity changes from step 11
43. Set A:RLLFS1 to A:CENFRQ. Unshort ARF3. Turn on DAC and High Level. Turn ARF3 to get about 10-20Volts.
44. Turn off 4-8 GHz Momentum cooling. Subtract 50 ps to trunk trombone of 4-8 Momentum system. Move plates to core orbit. Setup microwave spectrum analyzer to a harmonic of 628,888.
45. Turn off all transverse cooling
46. Bunch beam on ARF3 to 2300V (DAC 9.3). Move beam to 628888.
47. Debunch beam. Turn off ARF3. Short the gap.
48. Subtract 33 ps on to core settings for all transverse systems.
49. Turn on cooling
50. Adjust Tunes and coupling



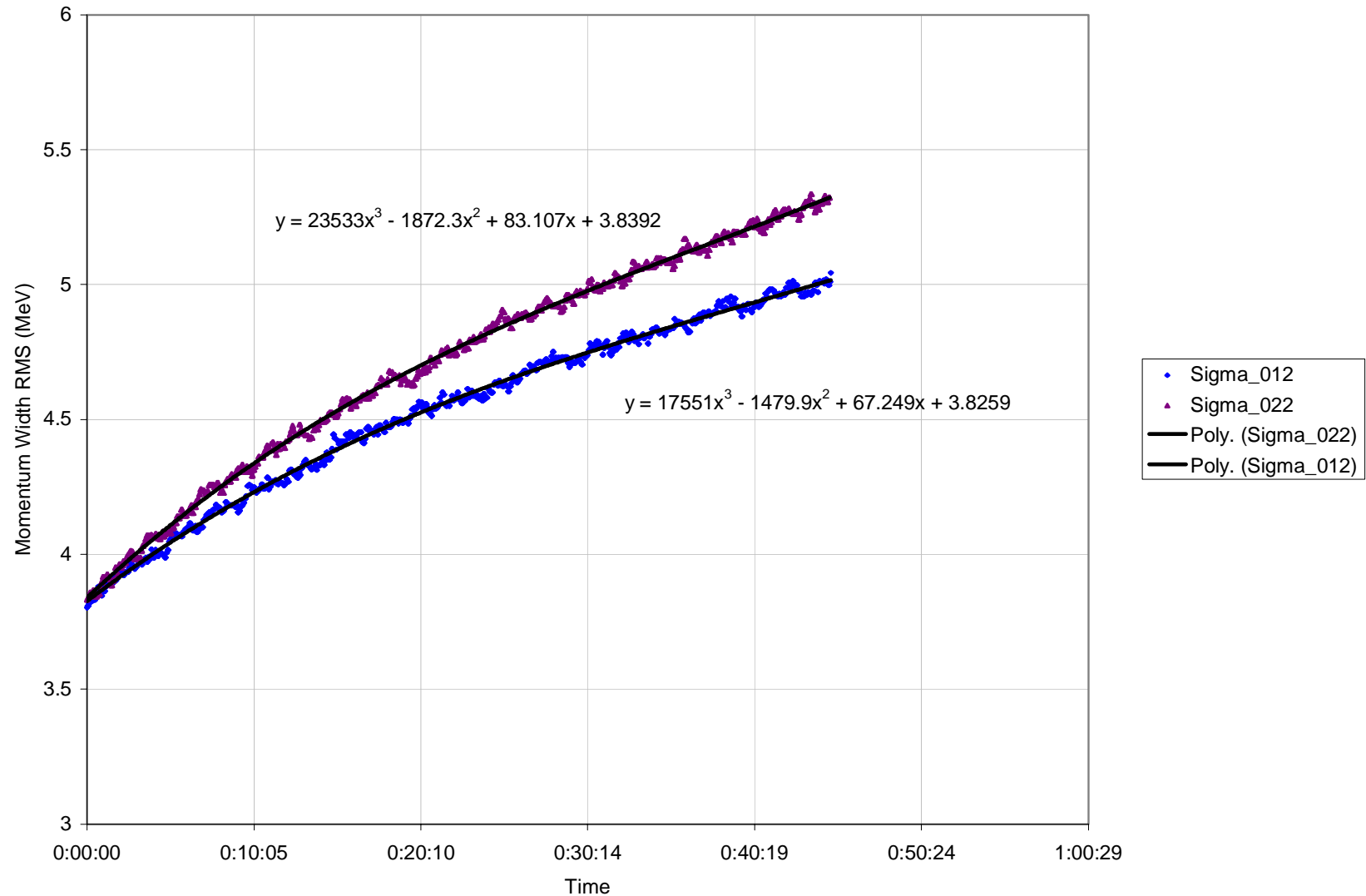
Measured Transverse Emittance Growth Rates



- Growth rates were measured with the same beam on the same day.
- Emittance initial conditions for both measurements are close but not exactly the same

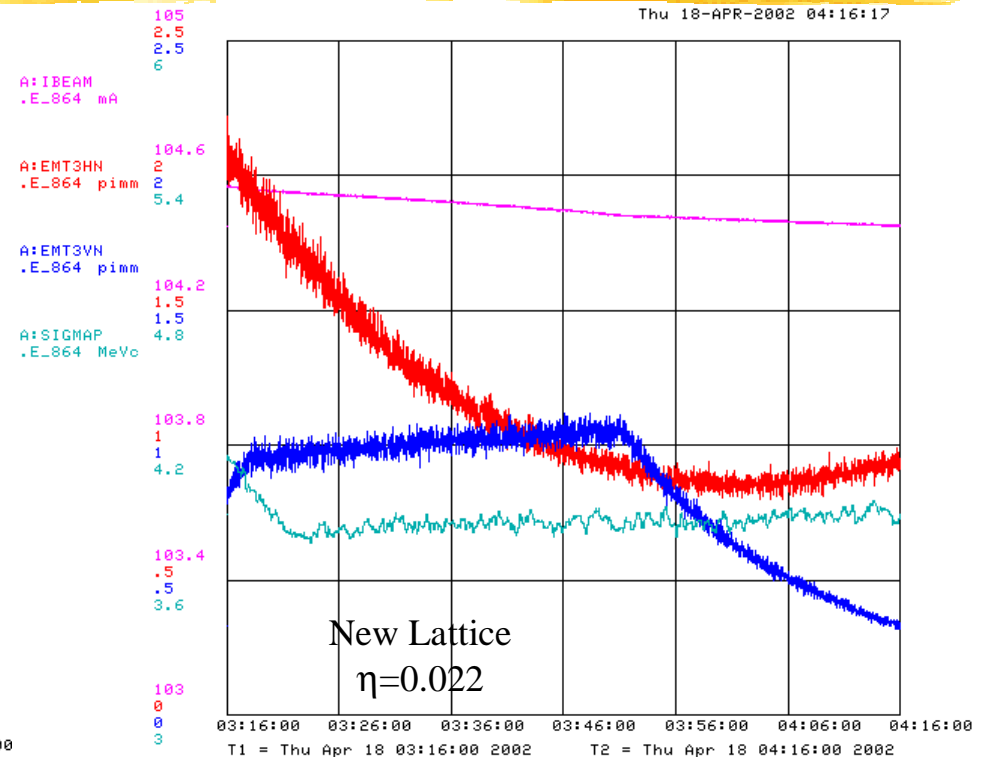
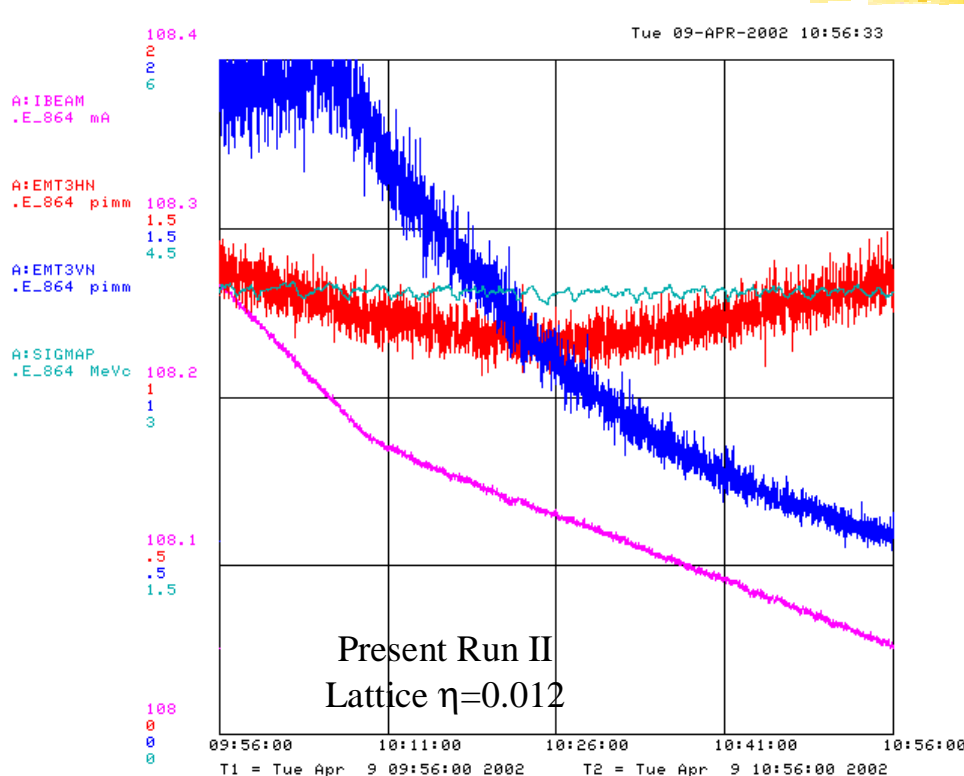


Measured Longitudinal Emittance Growth Rates





Horizontal Emittance vs. Vertical Emittance

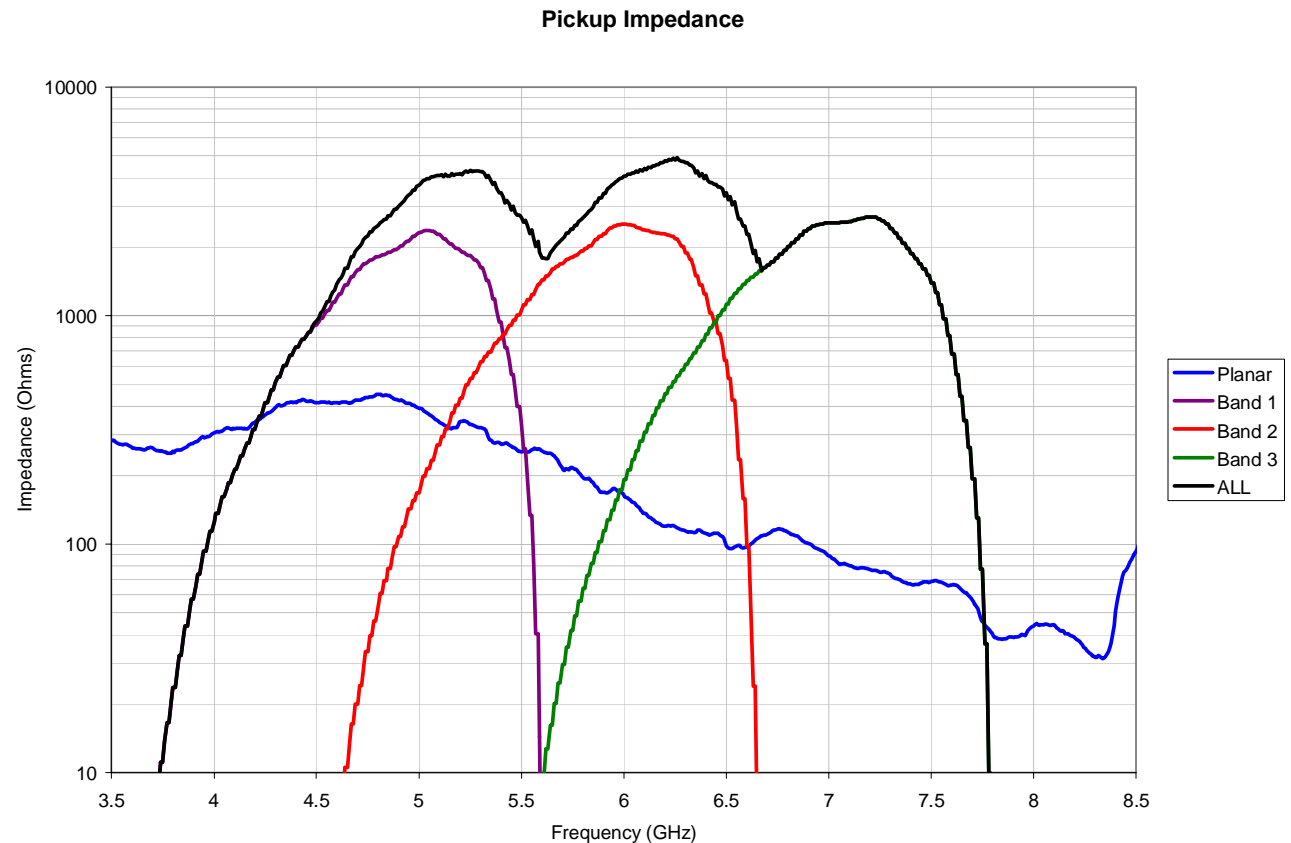


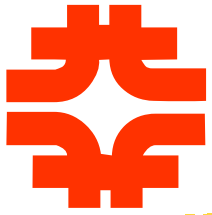
- Beam was heated vertically until the vertical emittance was much larger than the horizontal emittance (The horizontal cooling was on all the time)
- The vertical cooling was then turned on.
- When the vertical emittance reached the same value as the horizontal emittance, the horizontal emittance began to grow
- The asymptotic emittances with the new lattice are smaller than the present Run II lattice



Accumulator Core Cooling Upgrade

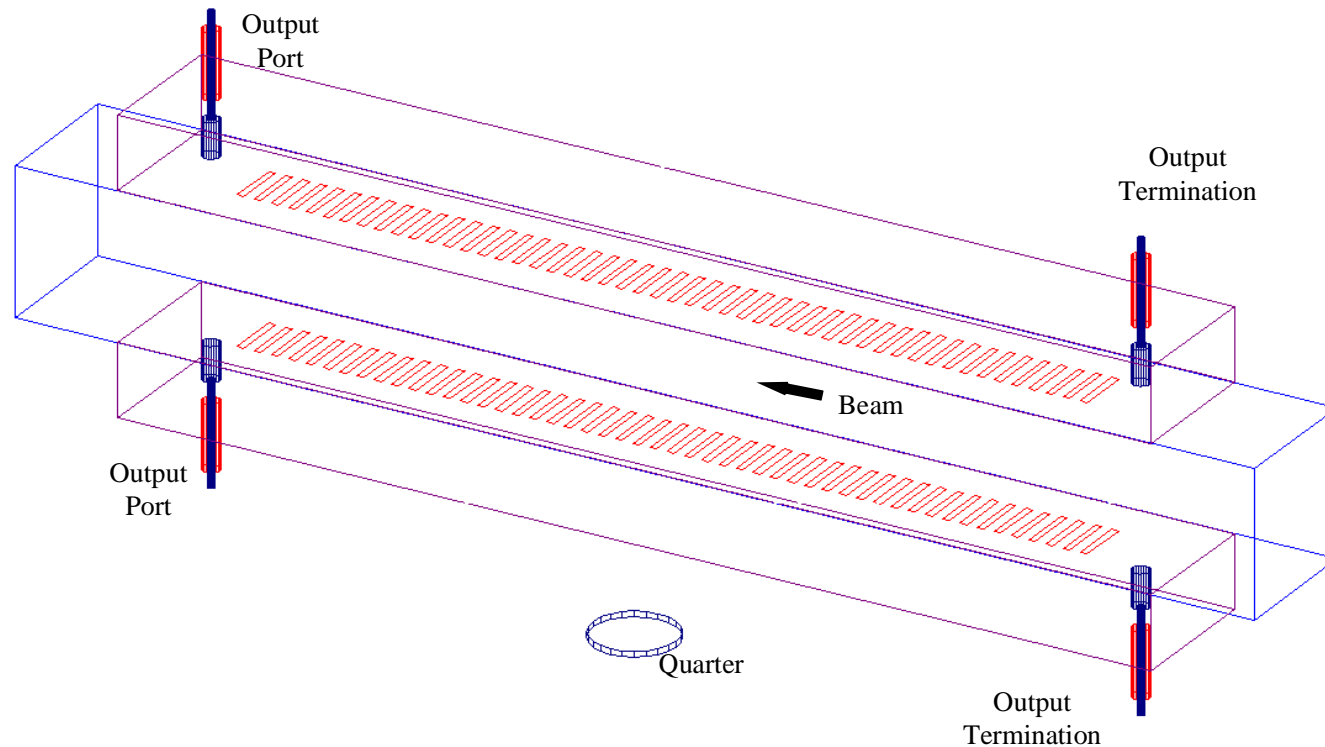
- Present system consists of a 2-4 GHz band and a 4-6 GHz band
 - ❑ The 2-4 GHz band is ineffective because of the small value of η
 - ❑ The 4-6 GHz band suffers from poor signal to noise.
- Replace both core bands with a 3 band Debuncher style system
 - ❑ Better sensitivity
 - ❑ More bandwidth (2x)
 - ❑ Better mixing factor (1.5x)
 - ❑ Installed in June 2002





Slow Wave Structures

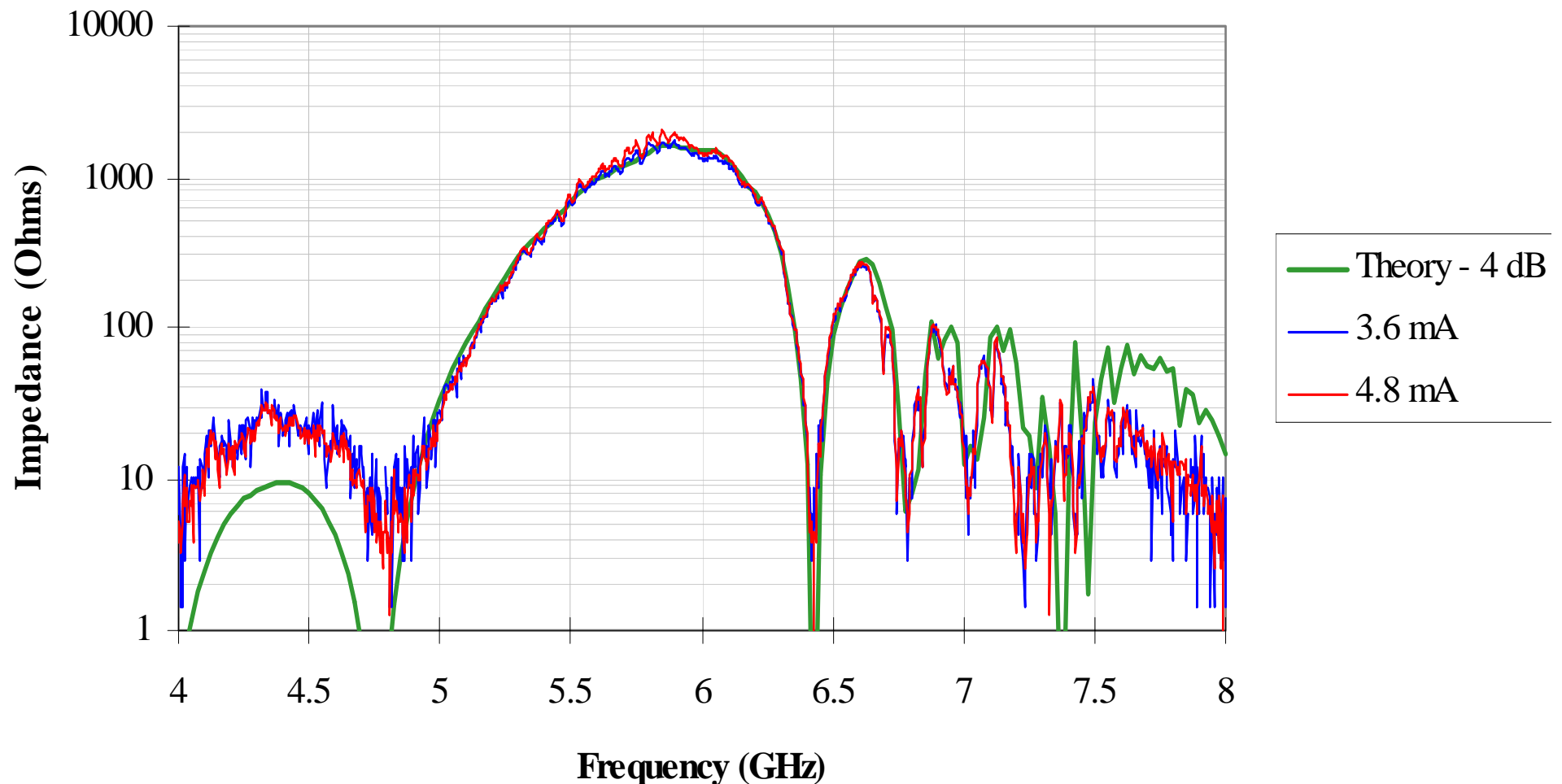
- The core cooling upgrade consists of slow-wave structures
- When the beam pipe can support a microwave mode (> 5 GHz in the Accumulator), binary combiner boards become ineffective
- The beam pipe of a slow-wave structure is designed to be above cutoff
- The slots of a slow-wave structure slow the phase velocity of the waveguide to match the beam velocity





Slow Wave Structures

- Slow wave structures are simple enough that their response can be accurately simulated with moment-method code.





Core Cooling Arrays





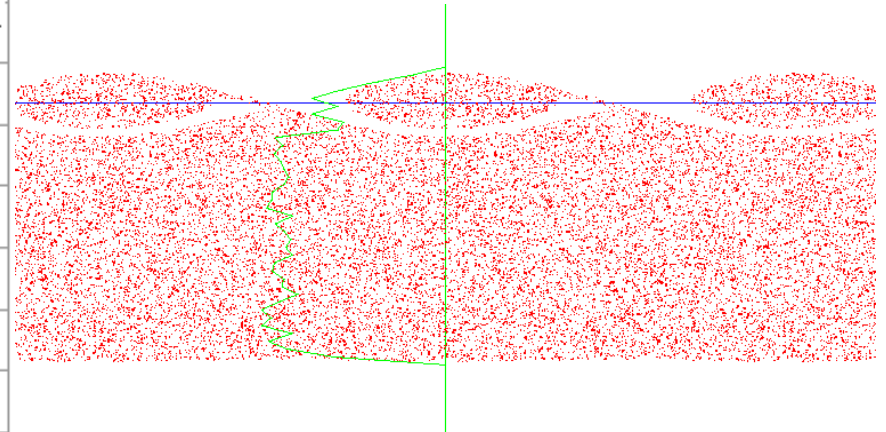
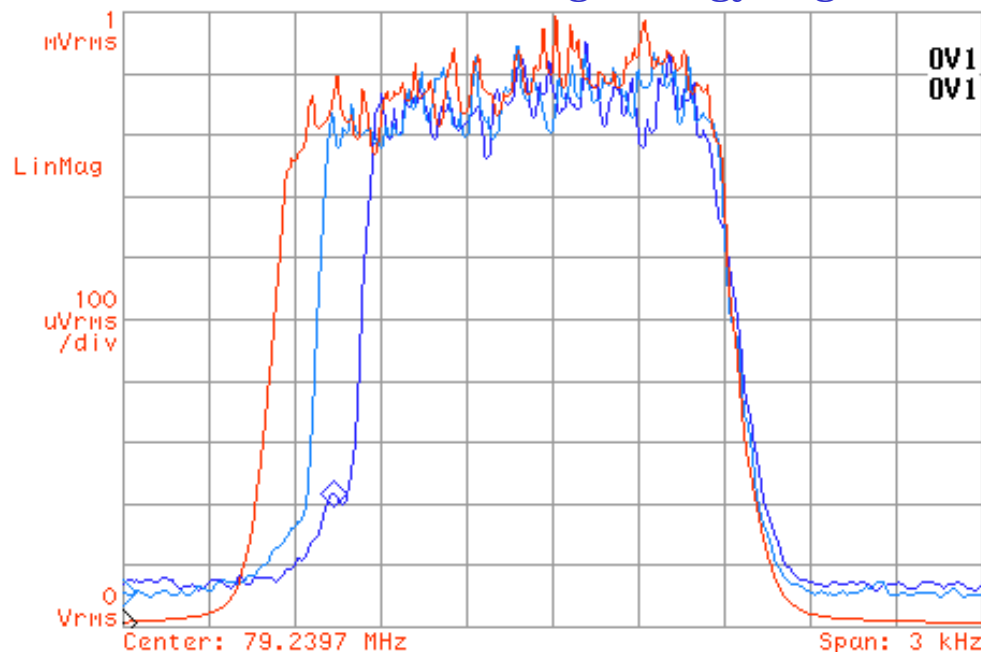
Core Cooling Tank

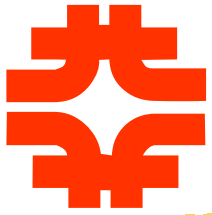




RF Extraction

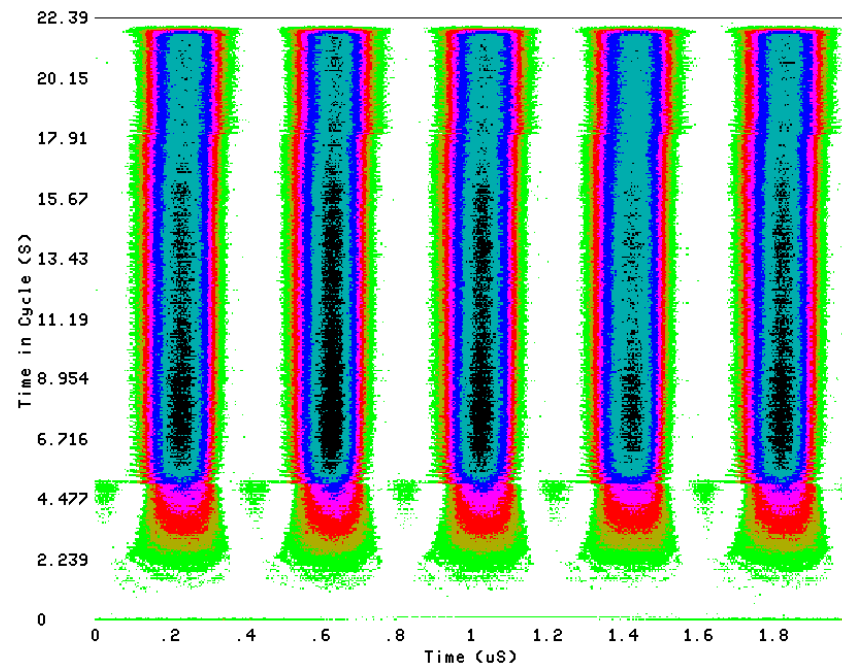
- Goal: Remove 4 bunches from the Accumulator during nine successive transfers
 - Each transfer should have the same number of pbars
 - Longitudinal emittance of each bunch should be < 1.0 eV-sec
 - Remove 90% of the stack
- Original Scheme
 - “Square” the momentum distribution with a chirped, filled bucket.
 - Extract off the high energy edge of the momentum distribution.





RF Extraction

- Drawbacks of the “squaring” technique
 - ❑ First derivative of frequency ramps not continuous.
 - Jumps in synchronous phase cause emittance dilution
 - ❑ RF bucket size is increased as the bucket is pulled away from the core
 - Soft edges in the momentum distribution will cause particles to be pulled in at edges of bucket giving rise to momentum dilution
 - ❑ Delays in shot setup after the core has been squared will give rise to very soft edges in the momentum distribution.
 - Momentum cooling cannot be turned on after the distribution is “squared”

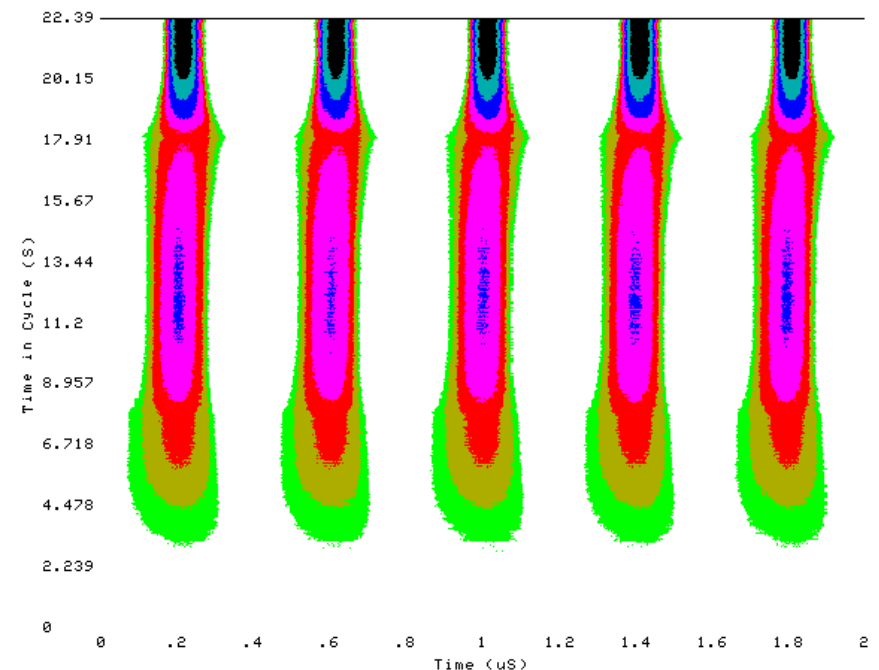
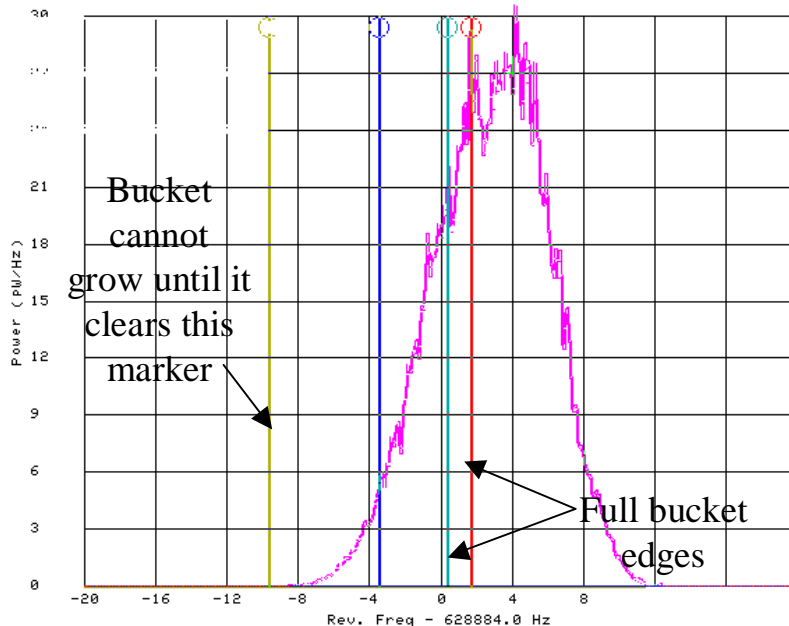


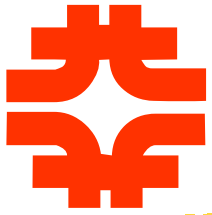
Bunch Profiles during
RF Extraction with
piece-wise continuous
frequency ramps



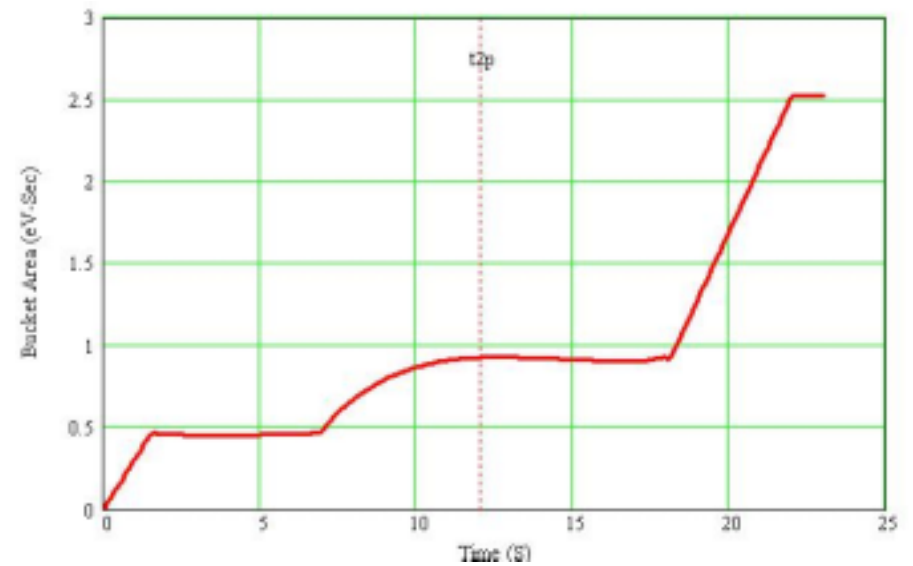
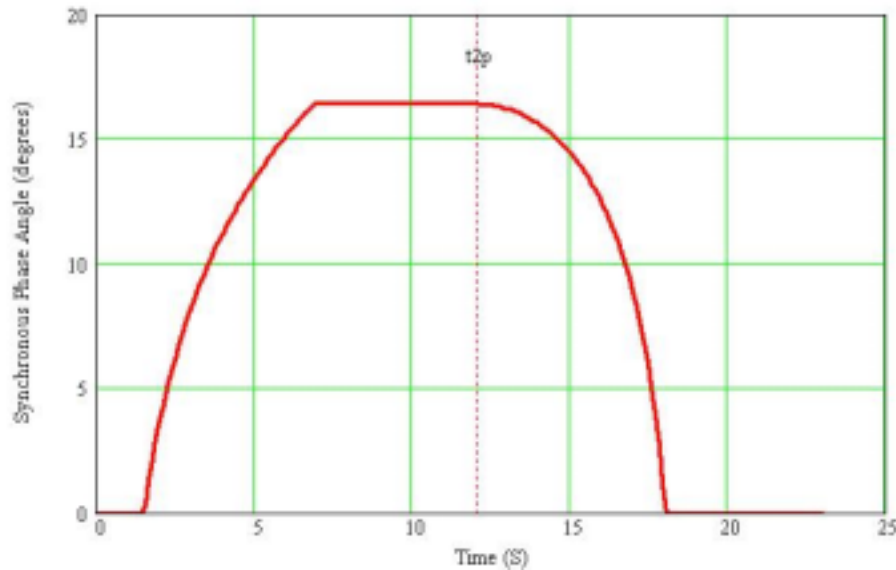
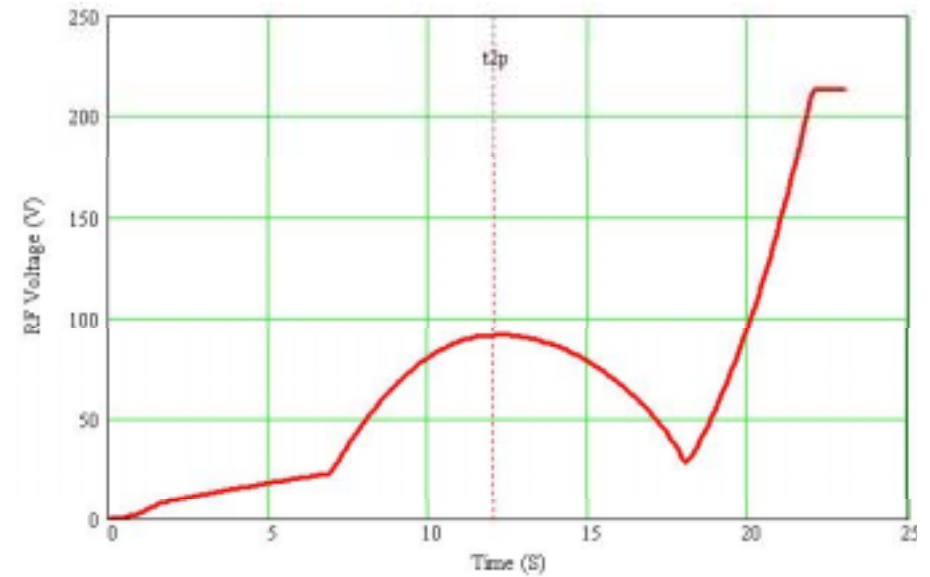
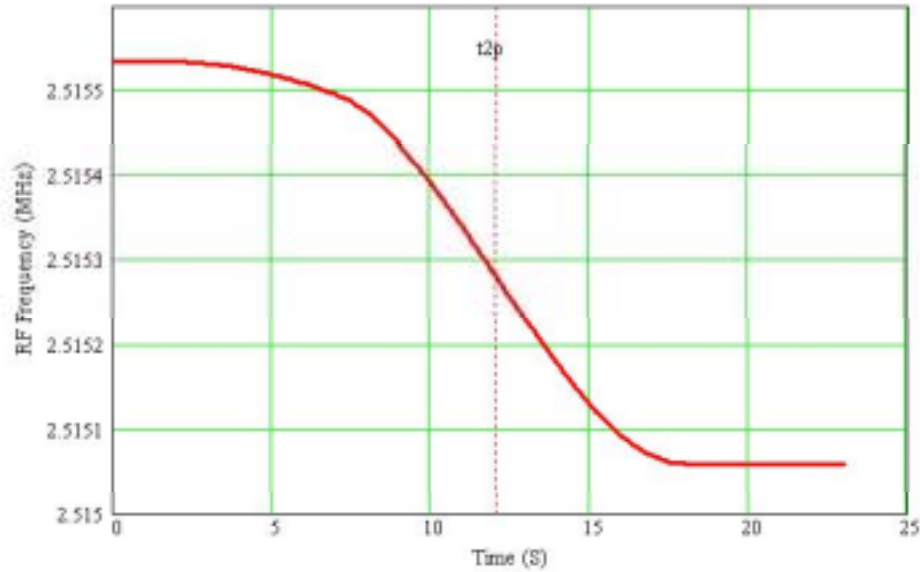
Changes in RF Extraction

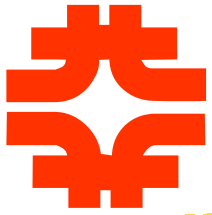
- No “squaring”.
- First derivative of frequency ramps are continuous
- A full bucket is grown near the middle of the core where the particle density is the highest. The bucket area needed is calculated from:
 - Desired fraction of stack to be extracted
 - real-time longitudinal schottky spectrum
- The bucket area is not increased from a full bucket until the entire bucket “clears” the high energy edge of the core.
- Once the bucket has cleared the core, the bucket area is increased while a constant synchronous phase is maintained.



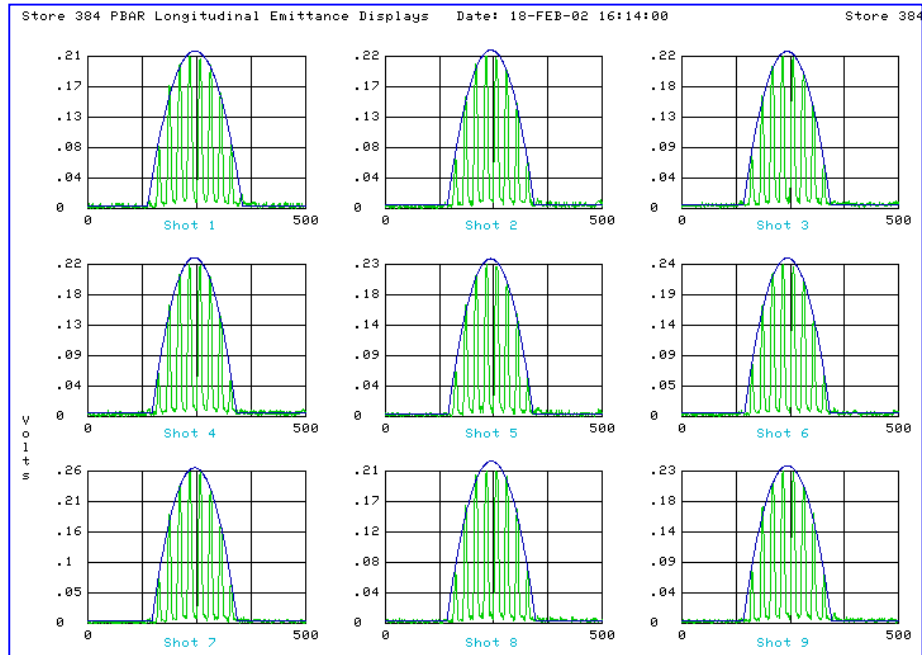


New RF Extraction Curves

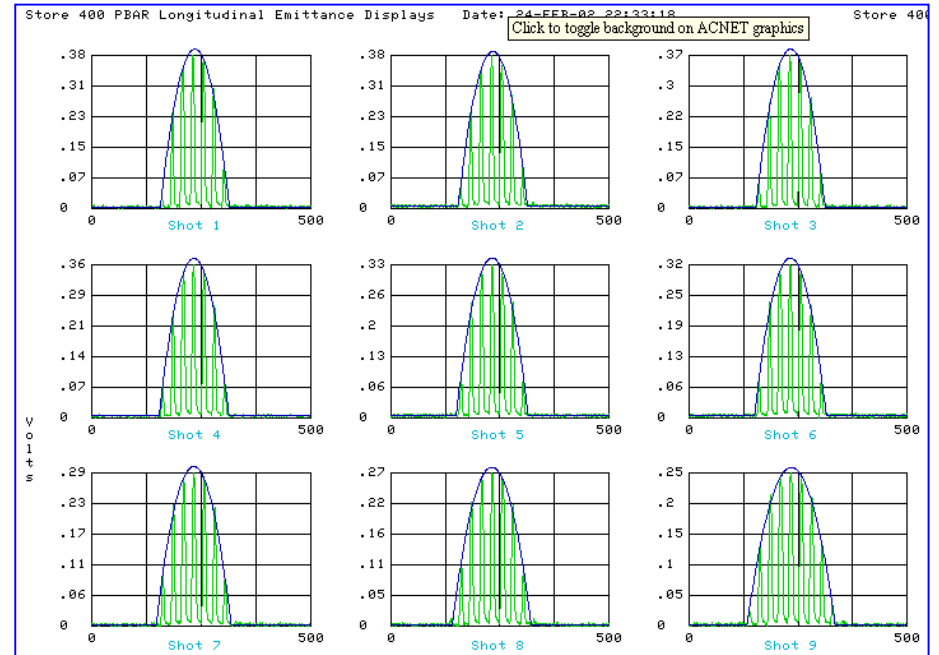




RF Extraction

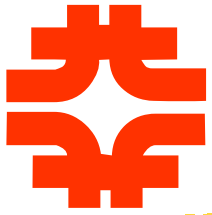


Old RF Curves



New RF Curves

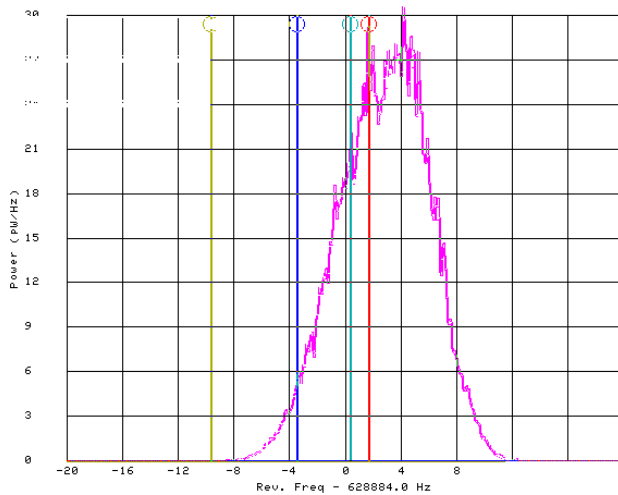
- Average longitudinal emittance reduced by ~35% with new RF curves
- No improvement in luminosity seen



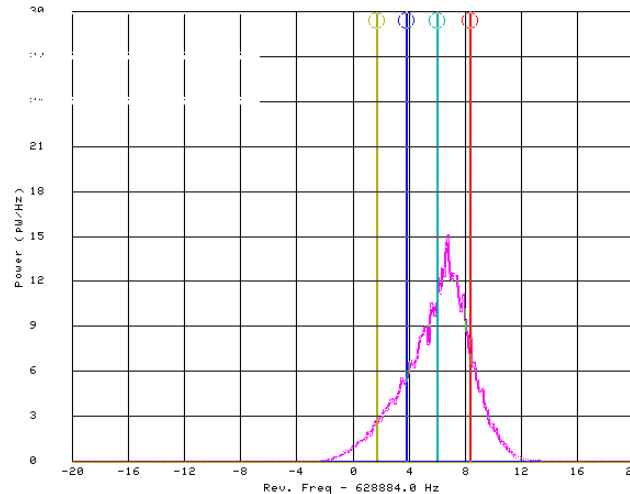
Remaining RF Extraction Problems

- Momentum width of core held large because of IBS
- Core is diluted after nine transfers
 - Need to optimize momentum cooling

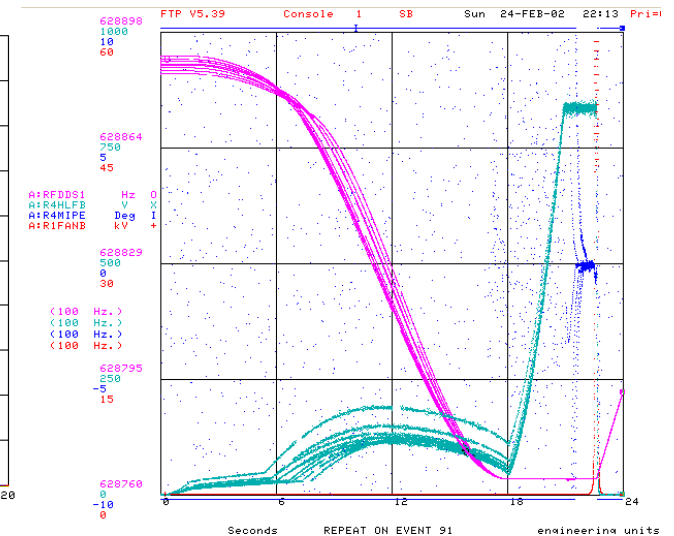
First Transfer



Ninth Transfer

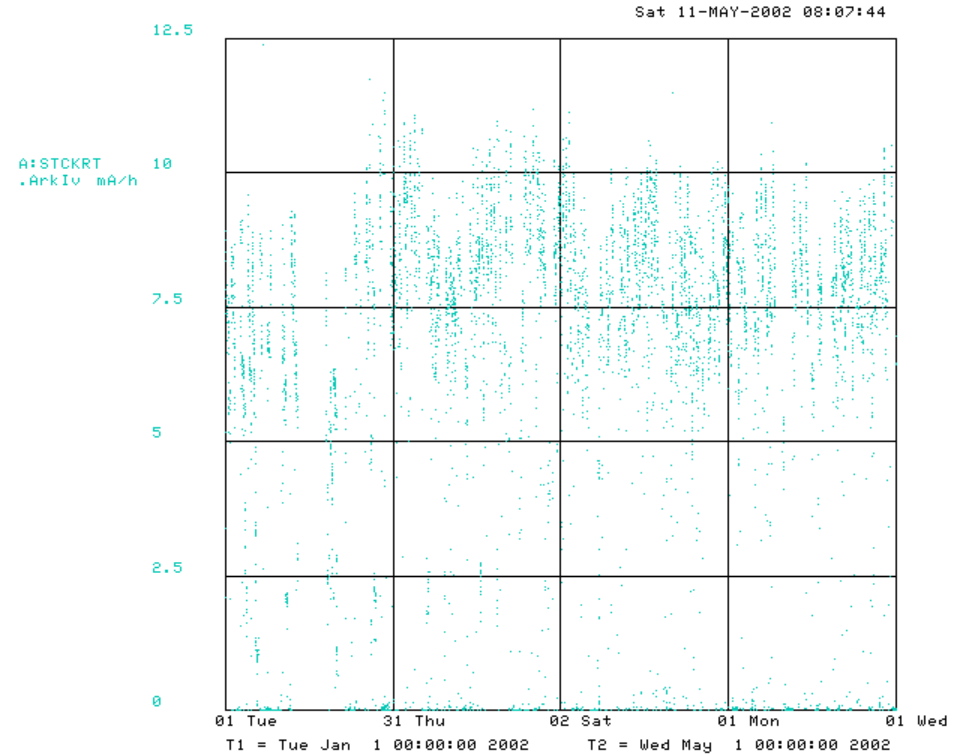
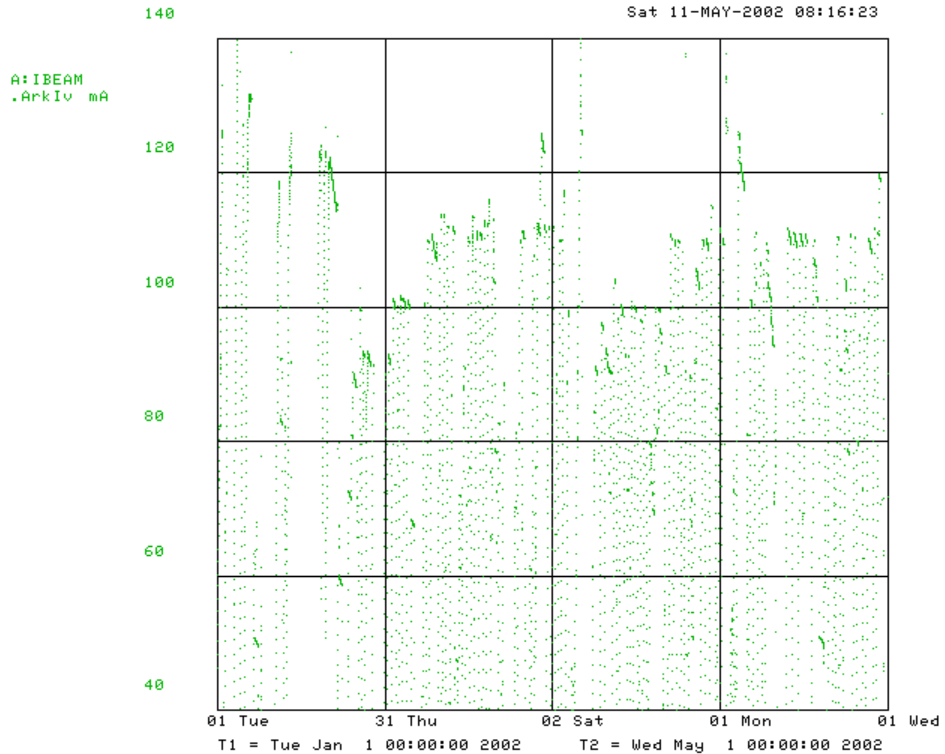


RF Curves

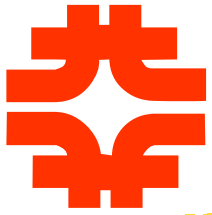




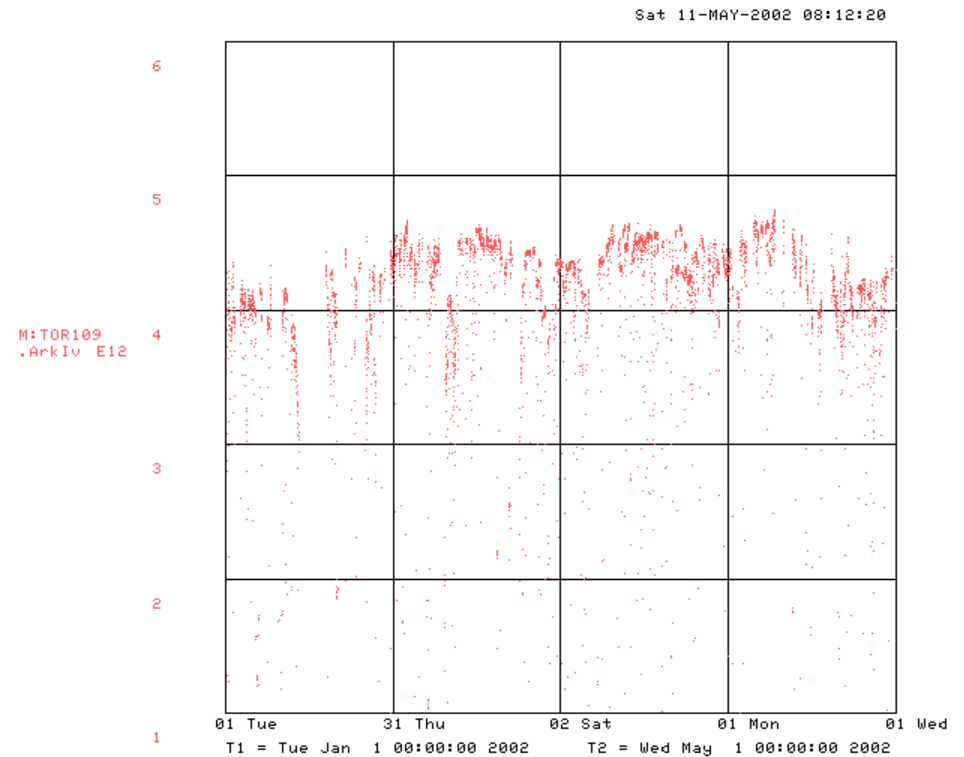
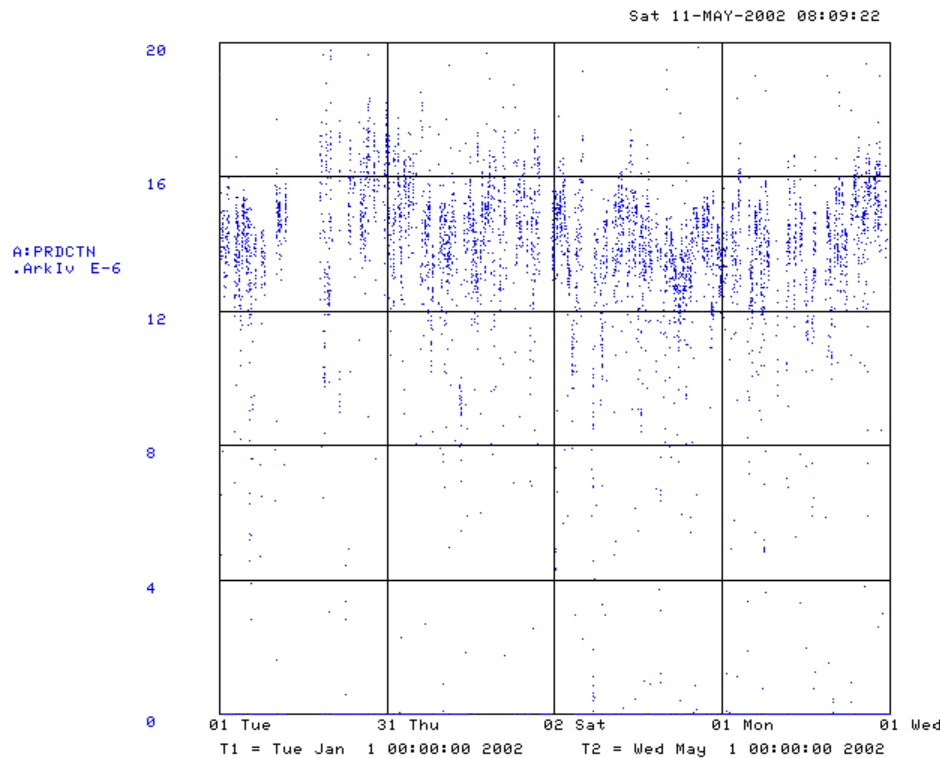
Pbar Production



- Average Stack size for TEVATRON Shots is about 110 mA
- Average Stack Rate is about 8.5 mA/hr
 - Typically start out at about 10 mA/hr at low stacks after shots
 - Typically stack at about 7.5 mA/hr near target stacks of 110 mA



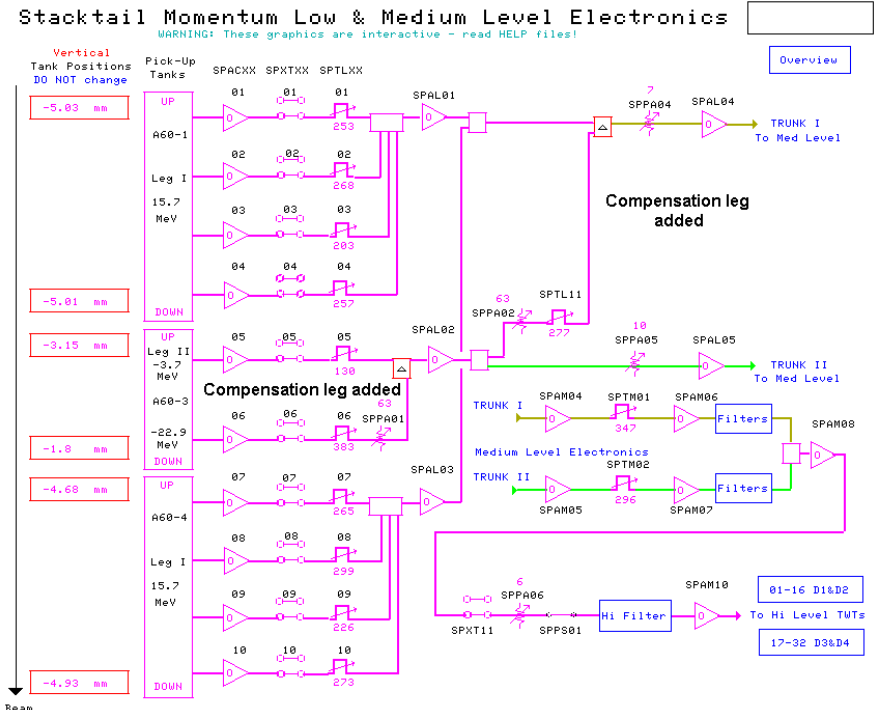
Pbar Production



- Peak Stack Rate is 11.2 mA/hr
 - ❑ Minimum Pbar production cycle time is 2.2 sec instead of design 1.5 sec.
 - ❑ Protons on target is 4.5E+12/batch instead of 5.0E+12/batch
 - ❑ $11.2 \times (2.2/1.5) \times (5/4.5) = 18.2 \text{ mA/hr}$



Stacktail Cooling Electronics



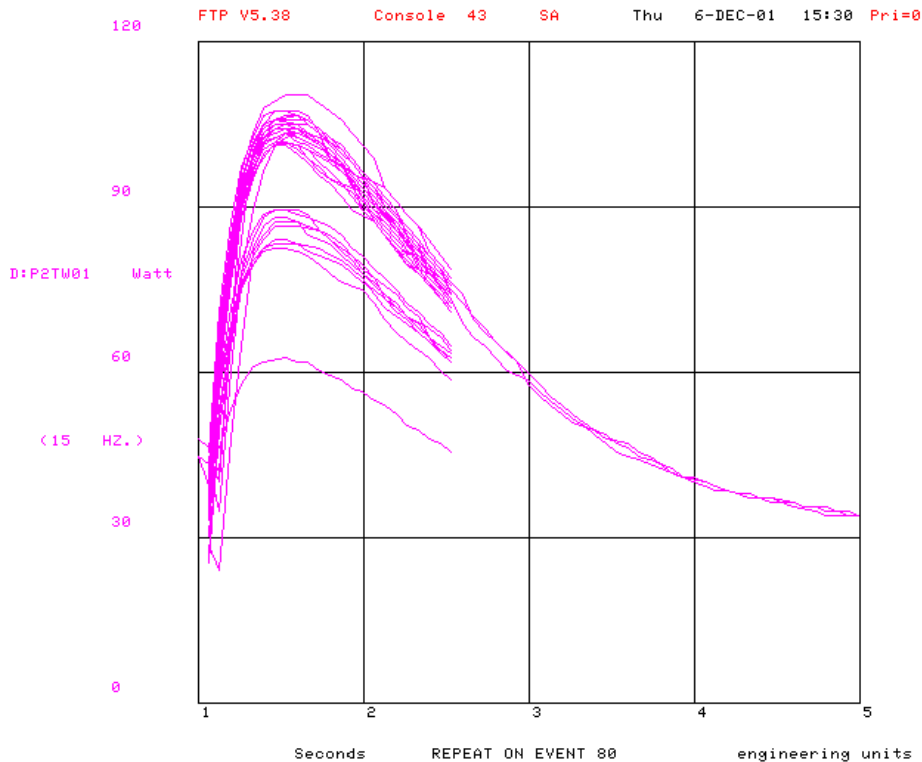
- Beam must be cleared off the Stacktail deposition orbit before next beam pulse.
- The more gain the Stacktail has, the faster the pulse will move.
 - ❑ The Stacktail gain is limited by system instabilities between the core beam and the injected beam
 - ❑ Additional compensation legs were installed in Dec. '01 in the stacktail electronics to mitigate the instabilities but have not been commissioned



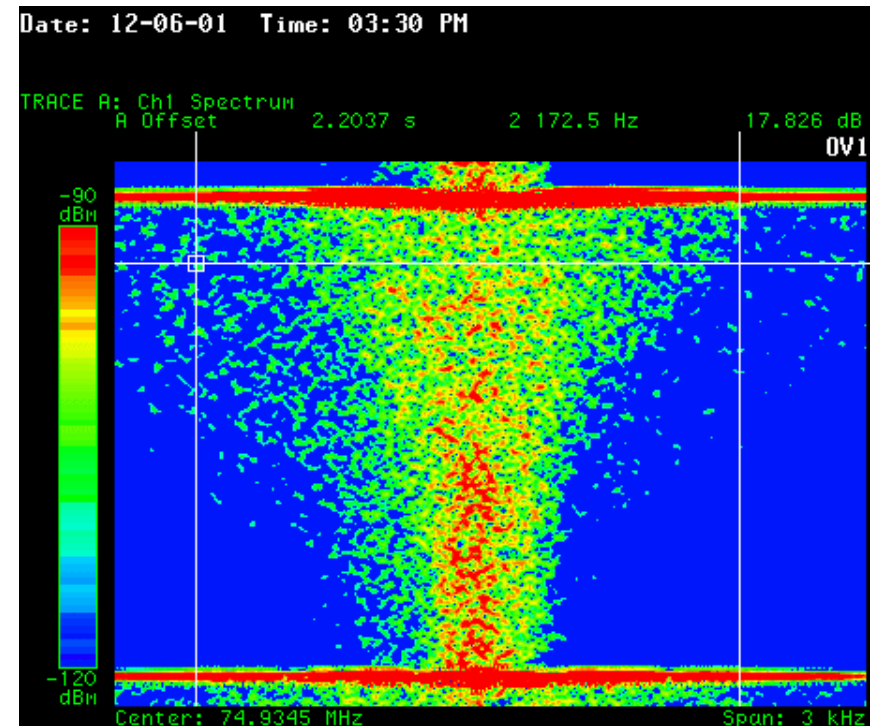
Why is the Cycle Time so Slow?

- For a given Stacktail gain, the larger the momentum spread of the injected pulse, the longer it takes to clear the pulse from the Stacktail Deposition orbit.
 - The momentum spread coming from the Debuncher is too large. Debuncher Momentum cooling is much slower than design.
 - Tighter narrow band filters are in production. These filters will reject more thermal noise and allow larger system gain.

Debuncher TWT power vs time



Debuncher Longitudinal Spectrum vs time





Summary

- The large horizontal emittance of the pbar stack is the most important problem facing the Pbar source.
- We hope to overcome this problem with:
 - Better core cooling
 - Dual lattice mode operation of the Accumulator
- The lack of emittance reduction in the Main Injector after recent dramatic transfer line lattice changes is a concern.
- After the emittance problem is mitigated, the reduction on pbar production cycle time will be the focus of the Pbar Source.